FOR FURTHER TRAN

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LASER-INDUCED THERMAL DAMAGE OF SKIN

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NOTICES

This final report was submitted by IIT Research Institute (IITRI), under contract F33615-76-C-0608, job order 7757-02-56 with the USAF School of Aerospace Medicine, Aerospace Medical Division, AFSC, Brooks Air Force Base, Texas. Captain Alan R. Mertz and Captain Kenneth L. Schepler (SAM/RZL) were the Laboratory Project Scientists-in-Charge.

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The animals involved in this study were procured, maintained, and used in accordance with the Animal Welfare Act of 1970 and the "Guide for the Care and Use of Laboratory Animals" prepared by the Institute of Laboratory Animal Resources - National Research Council.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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A computerized model was developed for predicting thermal damage of skin by laser exposures. Thermal, optical, and physiological data are presented for the model. Model predictions of extent of irreversible damage were compared with histologic determinations of the extent of damage produced in pig skin by CO_2 and ruby lasers.

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LASER-INDUCED THERMAL DAMAGE OF SKIN

INTRODUCTION

Numerous experimental investigations have been conducted to determine the degree of burns produced in skin by a variety of heat sources such as flames, hot water, and radiation (16,18,21,22).

Studies by Henriques (11), Stoll and Greene (21), and Takata (22) have used such data to develop burn criteria based upon transient temperatures. Moreover, a number of skin models exist (15,21) for computing skin damage caused by simple heating conditions--one-dimensional, surface absorption, etc. Unfortunately such models are not capable of handling a wide variety of phenomena. This is particularly true with variable spacial and temporal heating produced by lasers. What is needed is a model capable of accounting for two-dimensional heat deposition/transfer, blood flow, spacial/temporal variations of tissue properties, hair follicles, steam blisters, and evaporation of water. In this regard the Corneal Model (23), developed for the USAF School of Aerospace Medicine, Brooks Air Force Base, provides an excellent basis from which to build such a model. It is with this goal that this study is directed.

Specific objectives of the program are listed below:

- develop a comprehensive computerized model capable of predicting the extent and degree of skin burns produced by lasers
- identify data required by the code through literature searches and experiments
- conduct laser exposures of pigs and compare resultant damage with model predictions

The SKIN MODEL was designed to predict transient temperatures and thermal damage produced in skin by any radially symmetric laser beam of normal incidence. Basic to the model is the use of an implicit-explicit finite difference technique for computing transient temperatures. This technique was originally presented by Peaceman and Rachford (17). Since then it has been applied to cylindrical coordinates by Mainster et al. (14), and used by Takata et al. (23) to predict transient temperatures produced in eyes by laser irradiation.

Additional features provided in the SKIN MODEL are temporal changes in optical/thermal properties and thermal barriers created by steam blisters. Provisions have also been made for hot spots created by the interception of radiation by hair follicles. As with the eye model, thermal damage is predicted using Henriques damage integral (11). This criterion involves integrating temperature-dependent rates of damage with respect to time. Irreversible damage is predicted when the integral equals or exceeds a given value. The region of irreversible damage is predicted by evaluating damage at various depths and radii.

Data for the computerized model were obtained from the literature as well as from IITRI experiments. These data include thermal and optical properties of skin tissues, tissue densities and water content, blood flow rates, heat-transfer coefficients, and criteria for predicting the degree of burn and blister formation. Specific experiments conducted by IITRI are presented below:

- measurement of optical properties of excised pig skin
- measurement of heat-transfer coefficients associated with heat losses from moist and from dry skin to the surrounding air
- exposure of white skin pigs to CW CO_2 laser (nominal 5 watts) and to a pulsed ruby laser (nominal 25 joule pulses of 500-μsec duration and nominal 10 joule pulses of 50-μsec duration)

The pig experiments served to validate the model and to acquire additional data for the model. These data included criteria for the onset of blister formation and the degree of burn. Medical aspects of the pig exper[illegible]nts were supervised by Dr. Larry Zaneveld of the Univer[illegible] Illinois Medical Center. Extent of irreversible [illegible] measured histologically by Dr. Ward Richter of [illegible]y of Chicago.

Two-thirds of the predicted de[illegible] ir-reversible damage were within one [illegible] of the histological measurements of damage [illegible] ro-duced by the CO_2 laser. The CO_2 l[illegible] xpo[illegible] ved different beam diameters, las[illegible] [illegible]nes.

No damage was detected as a consequence of exposing pigs to single ruby laser pulses of 50 and 500 μsec. This result conflicts with model predictions and suggests appreciable energy was lost by some means not accounted for in the model. One possibility is attenuation of the laser beam by materials evolved from the skin surface. This appears likely in that a pronounced cracking sound accompanied each exposure. Wisps of smoke or vapor were observed immediately following several exposures.

DATA NEEDED BY THE SKIN MODEL

Prior to model development, a literature search was conducted. Of primary concern were property data with which to characterize skin and subcutaneous tissues such as

- reflectance
- absorption coefficients
- thermal conductivity
- specific heat
- density
- water content
- blood flow rates
- burn criteria

This endeavor involved computer searches of the following sources

1) SSIE -- Smithsonian Science Information Exchange
2) Biosis -- Biological Abstracts
3) Scisearch -- Current awareness of primary journals
4) Compendex -- Engineering Index
5) DDC -- Defense Documentation Center
6) NTIS -- National Technical Information Service

In this section we shall present pertinent data found in the literature along with IITRI measurements of the optical properties of pig skin. In addition heat-transfer coefficients are given for predicting the rates of heat transfer from skin surfaces to the surrounding air and across steam blisters.

IITRI Measurements of the Optical Properties of Pig Skin

Diffuse reflectance and absorption coefficients of various skin specimens were determined by exposing excised samples of pig skin to radiation of varying wavelengths and measuring the reflected and transmitted radiant energy. This determination involved use of the integrating sphere shown in Figure 1. Here measurements of the radiation from the sample or skin specimen are compared to that produced by the reference beam.

To separate the reflected radiation from the transmitted radiation, two power measurements were made with each specimen. One measurement was made with a black film on the unexposed side of the specimen to prevent escape of radiation transmitted through the specimen. The other measurement involved the specimen without the black backing.

Three types of tissues were used, namely

- normal epidermal/dermal specimens (5 different thicknesses)
- irreversibly thermal damaged epidermal/dermal specimens (3 different thicknesses)
- normal fat tissues (3 different thicknesses)

Skin was irreversibly damaged by placing a 70°C aluminum disk upon live skin. Contact was maintained for 1 minute.

All specimens were hairless and stretched in a sample holder by approximately 12% in one direction to ensure a flat surface. On the live animal the skin is stretched in two directions by approximately the same amount. Thus, the specimens were approximately 12% thicker than when on the live animal.

Percentages of the radiant energy diffusely reflected and transmitted through individual specimens are shown by the dashed curves of Figures 2, 3, and 4. The solid curve represents the sum of these curves. Absorption coefficients were obtained using Beer's Law namely

$$q = \exp(-\alpha z) \tag{1}$$

where q = fraction of absorbed radiant intensity transmitted through the specimen

α = absorption coefficient

z = specimen thickness

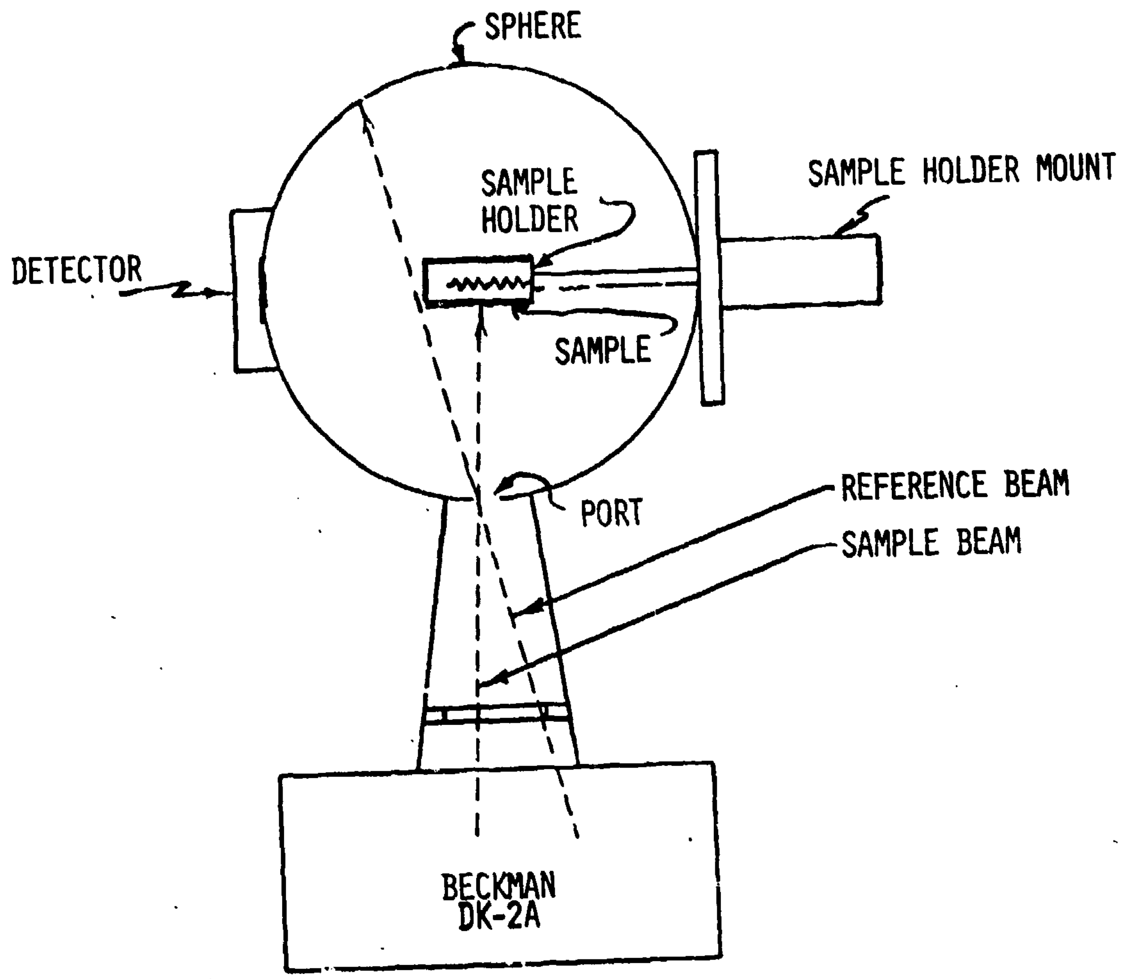


Figure 1. Schematic of integrating-sphere reflectometer.

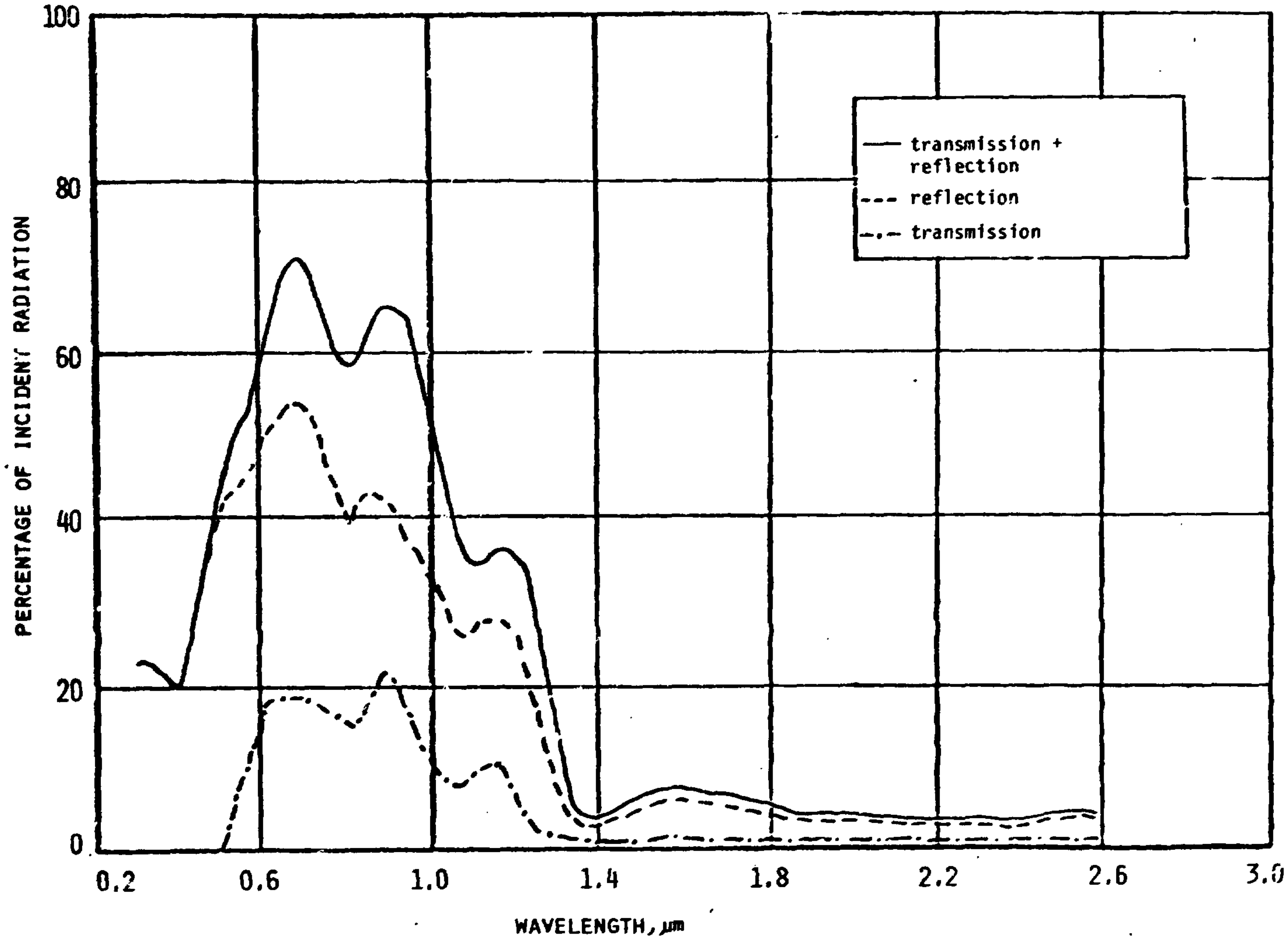


Figure 2. Optical data for undamaged pig skin (0.18-cm thick).

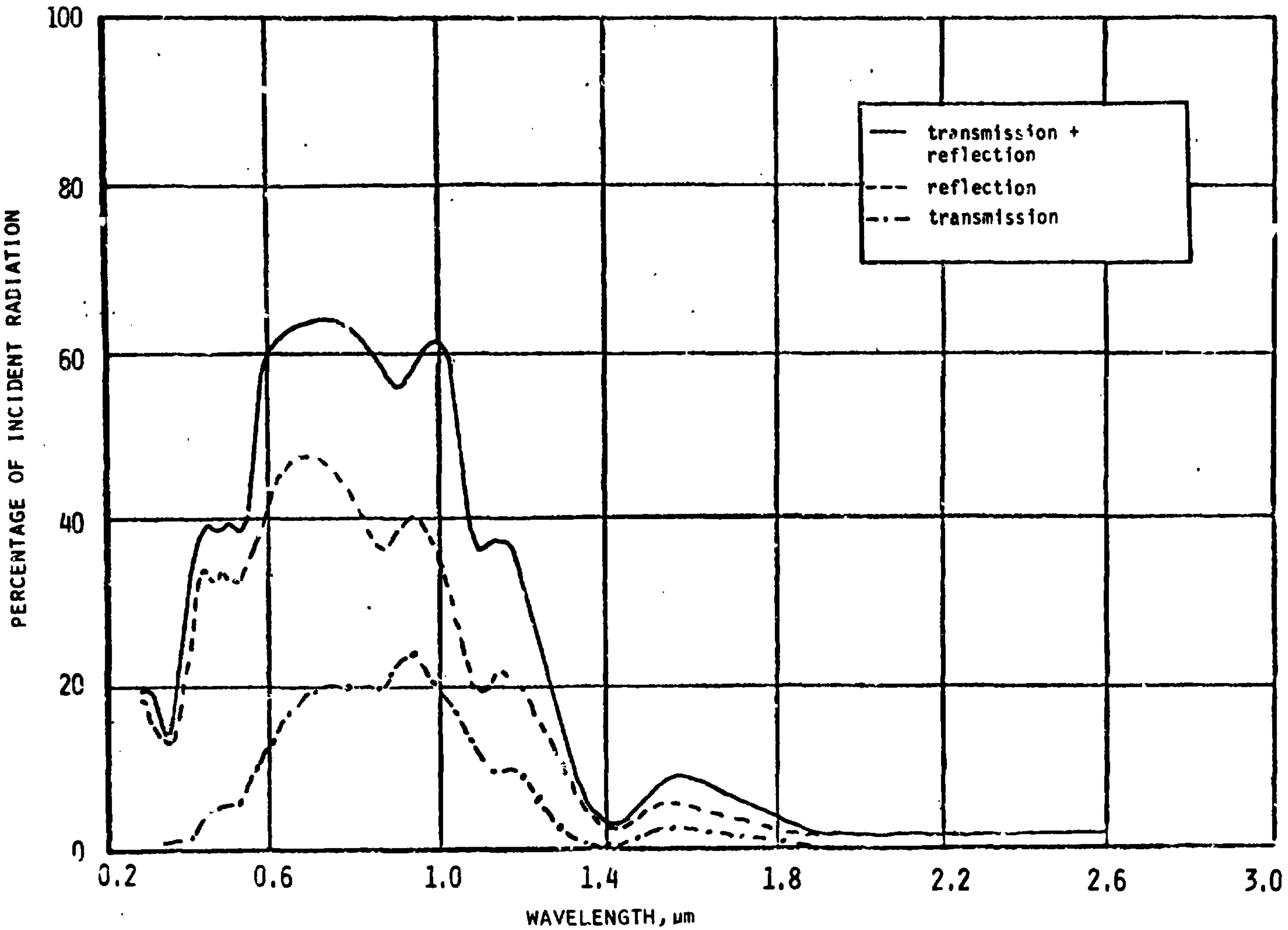


Figure 3. Optical data for thermally damaged pig skin (0.142-cm thick).

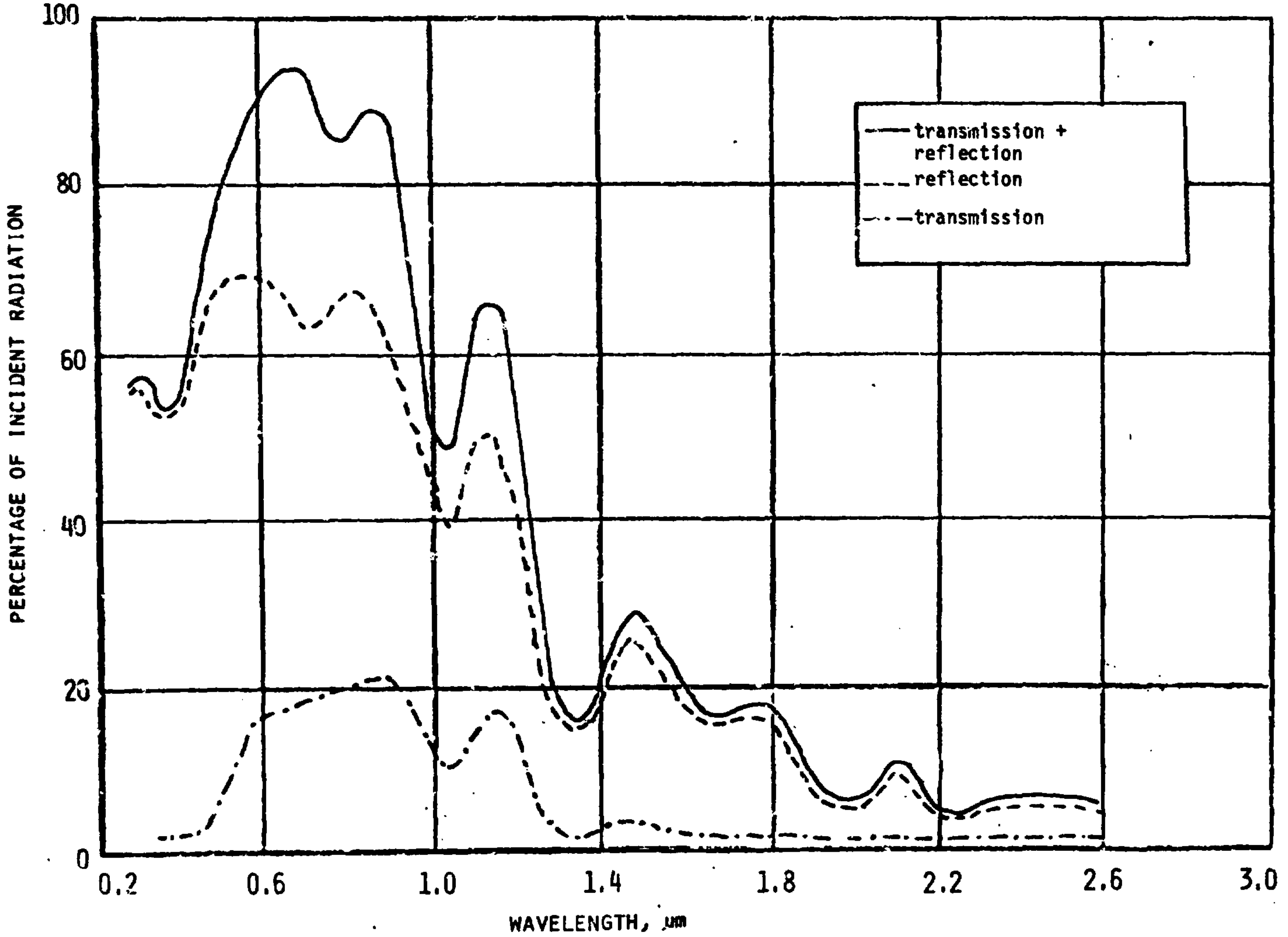


Figure 4. Optical data for pig fat (0.169-cm thick).

Solving equation 1 for α yields

$$\alpha = -\ln(q)/z \tag{2}$$

Absorption coefficients obtained from equation 2 are shown in Table 1 for 10 skin specimens over wavelengths ranging from 0.33 to 2.6 μm. It may be observed that the coefficients for the two fat specimens are in good agreement with each other while the coefficients for normal skin vary considerably. Particularly noteworthy are the higher absorption coefficients with the thinner specimens of skin which suggest greater absorption (percentagewise) by the epidermal and shallow dermal tissues than by the deeper dermal tissues. Such absorption is less evident with irreversibly damaged skin.

The coefficients for the deeper dermal tissues were determined by the following analysis using the absorption coefficients for the thinner specimens. The mean value α_o of the coefficients for the two thinner specimens shall be considered to apply to some unknown depth z_o, which remains to be determined. Beyond the depth z_o the coefficient will be represented by α_1. Using Beer's Law, the fraction of the nonreflected radiant flux passing through a depth z greater than z_o is given by

$$q = \exp-(\alpha_o z_o + \alpha_1(z-z_o)) \tag{3}$$

To determine the coefficient α_1 for the deeper thermal tissues, we shall use the transmission data for each of the three thicker specimens presented in Table 1. Each specimen will yield a somewhat different α_1 value according to the value selected for z_o. Basic to this analysis is the choice of z_o yielding the most consistent α_1 values for the three thickest specimens. For each trial z_o value, the deviations of the individual α_1 values from their mean value were squared and summed over each of the wavelengths considered. This procedure was performed using a variety of z_o values until the sum of the squares of the deviation was minimal. By this means the most consistent α_1 values were found to occur with a z_o value of 0.054 cm.

Results of this endeavor for normal skin are presented in Table 2. Included in Table 2 are the mean values of coefficients measured with irreversibly thermal damaged skin and with normal fat. In addition, mean reflection data are presented for the thicker specimens.

TABLE 1. EXPERIMENTALLY DETERMINED ABSORPTION COEFFICIENTS OF VARIOUS PIG TISSUES

Wavelengths (μm)	Absorption coefficients in cm^{-1} of skin to following depths in cm[a]					Absorption coefficients in cm^{-1} of coagulated skin to following depths in cm[a]			Absorption coefficients of fat for following specimen thicknesses in cm	
	0 to 0.046	0 to 0.053	0 to 0.133	0 to 0.157	0 to 0.181	0 to 0.087	0 to 0.091	0 to 0.142	0.130	0.169
0.33	53	73	26	-	-	57	49	-	24	20
0.35	49	64	26	34	-	50	59	26	20	20
0.40	45	57	21	29	-	46	57	32	18	21
0.45	29	33	18	25	24	26	28	23	15	16
0.50	24	25	14	18	19	19	20	18	12	14
0.55	23	24	12	16	16	18	20	18	12	12
0.60	19	19	11	12	12	16	14	14	11	11
0.65	17	17	10	11	10	14	12	11	11	11
0.70	17	16	10	10	10	14	12	11	11	10
0.80	16	17	8	10	9	10	12	10	10	9
0.90	16	17	8	10	9	9	11	10	10	10
1.00	16	16	9	10	9	9	11	10	10	10
1.10	15	16	8	11	9	9	11	11	10	10
1.20	17	17	11	15	11	11	14	14	12	12
1.30	18	19	12	17	14	14	15	16	12	12
1.40	41	43	33	29	28	34	32	35	27	23
1.50	38	40	33	29	27	35	35	35	20	20
1.60	28	27	21	24	19	23	23	21	18	19
1.70	27	27	20	26	20	23	23	23	34	20
1.80	33	32	20	25	6	27	25	28	29	20
1.90	57	60	36	26	34	45	43	-	40	23
2.00	63	73	-	26	34	71	-	49	33	23
2.10	49	51	-	26	32	47	47	44	34	23
2.20	44	47	-	26	32	43	43	42	-	23
2.30	53	58	-	25	34	49	59	42	32	20
2.40	70	-	-	24	28	59	64	41	35	21
2.50	79	-	-	23	-	57	68	44	40	23
2.60	79	-	-	-	-	54	68	49	40	23

[a]Depths measured from surface of skin.

Use of two absorption coefficients for the skin is consistent with the measurements involving fair-skinned human beings shown in Figure 5 for wavelengths from 0.3 to 1.0 μm. Beyond 1.0 μm, Figure 5 presents only a single absorption coefficient and is in variance with data presented in Table 2. On comparing the results of Figure 5 with the coefficients of Table 2 for the shorter wavelengths and the mean coefficients of Table 1 for the longer wavelengths, observe that our values are lower across the entire spectrum. This observation suggests that the skin of young pigs transmits radiation better than fair-skinned human beings.

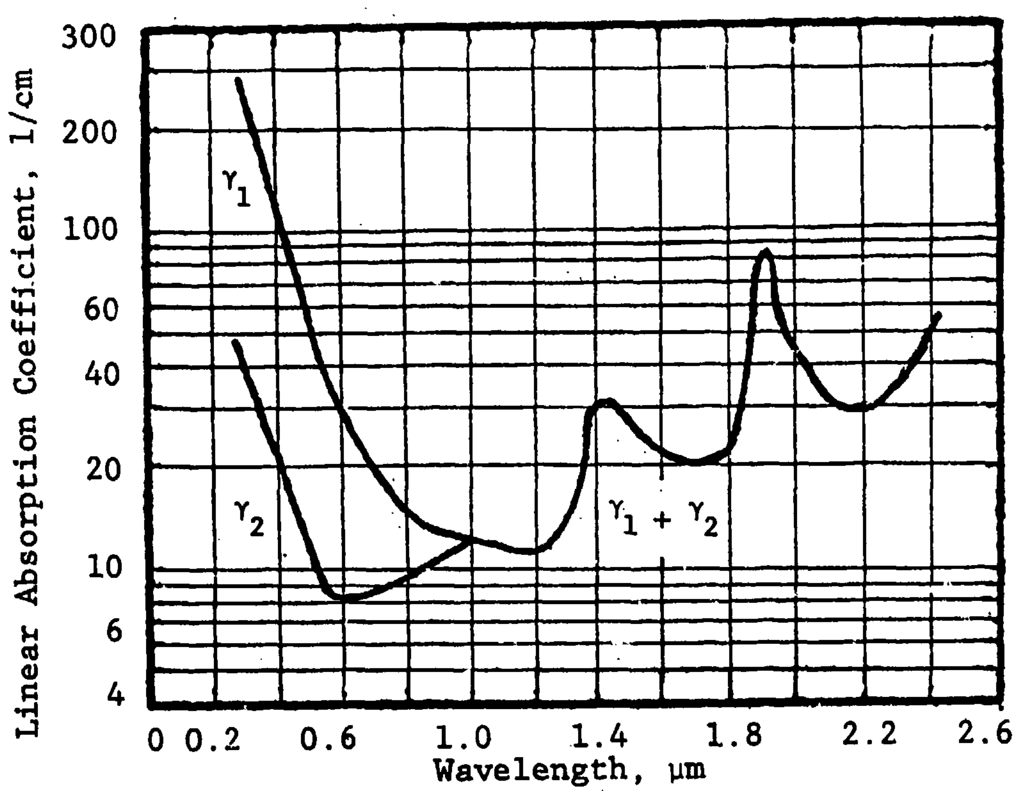


Figure 5. Linear absorption coefficients of fair-skinned humans from in vivo measurements (ref. 6).

- γ_1 curve for superficial skin layers
- γ_2 curve for deeper tissues

Before concluding, it is important to recognize that the skin specimens were 12% thinner when on the live animal. Hence the critical depth of 0.054 cm presented in Table 2 should be reduced by 12% to 0.048 cm. Coefficients remain the same.

TABLE 2. SUMMARY OF OPTICAL PROPERTIES FOR VARIOUS PIG TISSUES

Wavelengths (μm)	Normal skin			Thermally damaged skin		Fat
	Reflection[a] (%)	Absorption coefficients in cm^{-1} of skin between following depths in cm^{-1}		Reflection[b] (%)	Absorption coefficient in cm^{-1}	Absorption coefficient in cm^{-1}
		0 to 0.054 cm	deeper than 0.054 cm			
0.33	35	64	1	33	53	22
0.35	36	57	14	31	45	20
0.40	33	51	10	26	39	20
0.45	42	31	17	38	26	15
0.50	51	25	12	42	19	13
0.55	50	23	10	40	18	12
0.60	58	19	9	9	15	11
0.65	60	17	7	50	12	11
0.70	60	17	7	50	12	10
0.80	58	17	5	49	10	10
0.90	52	17	5	45	10	10
1.00	48	16	6	46	10	10
1.10	43	16	6	39	10	10
1.20	32	17	10	29	12	12
1.30	21	18	12	17	15	12
1.40	5	64	24	5	34	25
1.50	5	40	24	5	35	20
1.60	8	40	18	9	24	18
1.70	8	27	20	8	25	27
1.80	6	32	20	6	27	25
1.90	4	5	18	3	44	31
2.00	4	6	11	3	60	28
2.10	4	50	19	4	46	28
2.20	4	46	21	3	43	23
2.30	3	55	17	1	50	26
2.40	3	70	6	2	54	28
2.50	3	7	7	2	57	32
2.60	3	7	-	2	57	31

[a]Mean value of 3 specimens ranging in thickness from 0.133 to 0.181 cm.

[b]Mean value of 3 specimens ranging in thickness from 0.087 to 0.142 cm.

Optical Properties of Human Skin and Water

Figures 5 through 7 present optical properties of human skin found in the literature. Figure 6 shows the reflectance of white and black skin over wavelengths from 0.4 to 40.0 μm (10). Notice that skin pigmentation is important for wavelengths below about 2 μm. Beyond 2 μm pigmentation is not important.

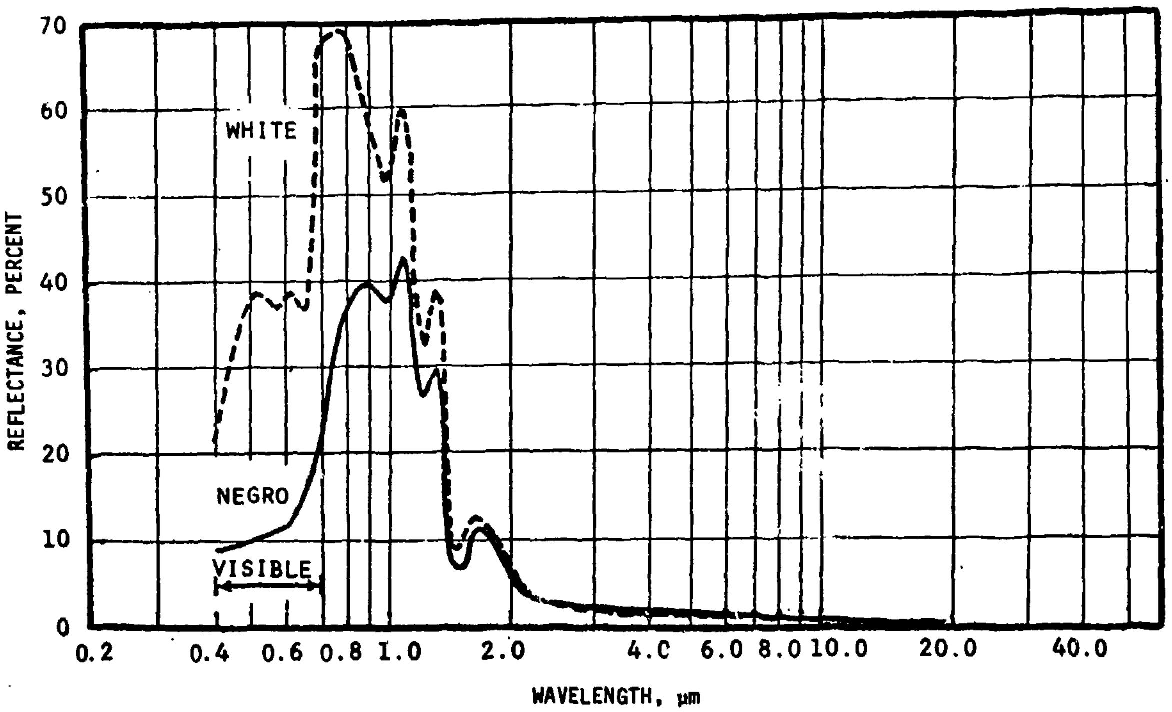


Figure 6. Spectral reflectance of white and negro skin (from ref. 10)

Figure 7 presents transmittance data (8) for a 0.003-cm thick layer of wet and dry epidermis. IITRI calculations of the absorption coefficient are presented at the right of the figure. Over wavelengths from 1.0 to 2.4 μm, it may be observed that the coefficients for thin epidermal layers are much larger than the coefficients for the entire skin presented in Figure 5. This observation suggests there should be two absorption coefficients for the skin--one for the outer epidermal layer and one for the remainder of the skin as was found for pig skin. Table 3 presents our best estimates of the reflectance and absorption coefficients of human skin based upon the literature, and IITRI measurements using pig skin.

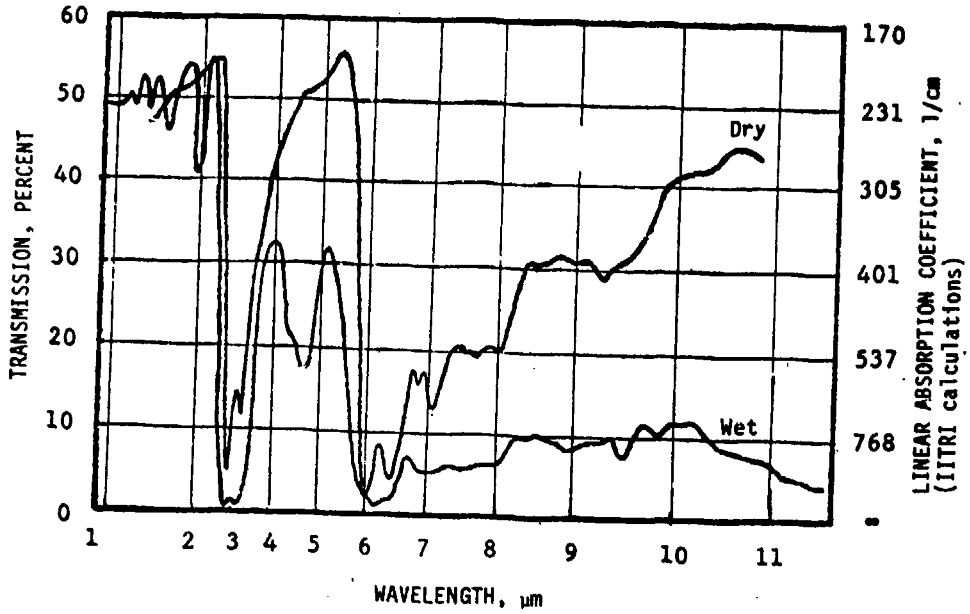


Figure 7. Transmission spectrum of human epidermis (0.003 cm thick), wet and dry (from ref. 8).

Absorption coefficients could not be found for skin tissues deeper than 0.003 cm for wavelengths beyond 2.4 μm. In this regard we recommend using the values for water shown in Table 4 (7). This recommendation is made for two reasons. First, the fraction of the radiant intensity passing through the thin (0.003 cm) outer layer of epidermis is usually small at the longer wavelengths. Secondly, water present in the tissues has very large absorption values at wavelengths beyond 2.4 μm. The result is very shallow penetration of the radiant energy beyond the relatively thin epidermal layer. Epidermal layers are of the order of 0.01 cm thick as contrasted with values of the order of 0.2 cm for dermal layers.

Thermal Properties of Skin

The most important parameter affecting the thermal properties is the amount of water in the tissues. Water is important in that it is an excellent heat sink as well as a relatively good conductor of heat. By comparison, the effects of temperature upon thermal properties are of secondary importance and hence will not be considered.

TABLE 3. OPTICAL PROPERTIES OF HUMAN SKIN

Wavelength, (µm)	Reflection[a] (%) White	Reflection[a] (%) Negro	Absorption coefficients (normal tissues), 1/cm: Sweat[b]	Outer 0.003 cm of epidermis[c]	Remaining skin[d]	Fat[e]	Absorption coefficients[e], (irreversibly damaged tissues), 1/cm
0.33	(35)	-	0	200	40	22	53
0.40	22	9	0	110	21	20	39
0.50	38	10	0	55	13	13	19
0.60	38	12	0	29	12	12	15
0.65	37	15	0	25	8	11	12
0.70	68	22	0	40	9	10	12
0.80	67	37	0	16	10	10	10
0.90	57	39	0	13	12	10	10
1.00	53	38	0	238	13	10	10
1.10	58	40	0	231	13	10	10
1.20	58	40	1	233	12	12	12
1.42	35	27	1	217	31	24	34
1.70	13	11	7	231	20	27	25
1.85	11	9	23	205	40	28	35
2.20	3	3	17	202	30	23	43
2.40	3	3	50	244	50	28	54
3.00	2	2	11394	1448	-	-	-
4.00	2	2	145	380	-	-	-
4.70	2	2	420	572	-	-	-
5.00	2	2	312	401	-	-	-
6.00	2	2	2241	1230	-	-	-
7.00	1	1	574	999	-	-	-
8.00	1	1	539	921	-	-	-
9.00	1	1	537	821	-	-	-
10.00	1	1	638	727	-	-	-
11.00	1	1	1106	911	-	-	-

[a]Values from Figure 6, reflection at 0.33 µm from Table 2.

[b]Results for sweat taken from Table 4 for water.

[c]Values below 1 µm from Figure 5; other values from Figure 7.

[d]Values from Figure 5.

[e]Values from Table 2.

TABLE 4. ABSORPTION CONSTANTS OF WATER (ref. 7)

λ (μm)	α (cm^{-1})	λ (μm)	α (cm^{-1})	λ (μm)	α (cm^{-1})
0.200	$6.9115 \cdot 10^{-2}$	0.900	$6.7858 \cdot 10^{-2}$	3.400	$7.2072 \cdot 10^{2}$
0.225	$2.7367 \cdot 10^{-2}$	0.925	$1.4400 \cdot 10^{-1}$	3.450	$4.8080 \cdot 10^{2}$
0.250	$1.6839 \cdot 10^{-2}$	0.950	$3.8757 \cdot 10^{-1}$	3.500	$3.3750 \cdot 10^{2}$
0.275	$1.0739 \cdot 10^{-2}$	0.975	$4.4852 \cdot 10^{-1}$	3.600	$1.7977 \cdot 10^{2}$
0.300	$6.7021 \cdot 10^{-3}$	1.000	$3.6317 \cdot 10^{-1}$	3.700	$1.2227 \cdot 10^{2}$
0.325	$4.1759 \cdot 10^{-3}$	1.200	1.0357	3.800	$1.1244 \cdot 10^{2}$
0.350	$2.3338 \cdot 10^{-3}$	1.400	$1.2387 \cdot 10^{+1}$	3.900	$1.2244 \cdot 10^{2}$
0.375	$1.1729 \cdot 10^{-3}$	1.600	6.7152	4.000	$1.4451 \cdot 10^{2}$
0.400	$5.8434 \cdot 10^{-4}$	1.800	8.0285	4.100	$1.7225 \cdot 10^{2}$
0.425	$3.8438 \cdot 10^{-4}$	2.000	$6.9115 \cdot 10^{+1}$	4.200	$2.0585 \cdot 10^{2}$
0.450	$2.8484 \cdot 10^{-4}$	2.200	$1.6508 \cdot 10^{+1}$	4.300	$2.4694 \cdot 10^{2}$
0.475	$2.4736 \cdot 10^{-4}$	2.400	$5.0056 \cdot 10^{+1}$	4.400	$2.9417 \cdot 10^{2}$
0.500	$2.5133 \cdot 10^{-4}$	2.600	$1.5321 \cdot 10^{+2}$	4.500	$3.7420 \cdot 10^{2}$
0.525	$3.1595 \cdot 10^{-4}$	2.650	$3.1772 \cdot 10^{2}$	4.600	$4.0158 \cdot 10^{2}$
0.550	$4.4782 \cdot 10^{-4}$	2.700	$8.8430 \cdot 10^{2}$	4.700	$4.1977 \cdot 10^{2}$
0.575	$7.8676 \cdot 10^{-4}$	2.750	$2.6961 \cdot 10^{3}$	4.800	$3.9270 \cdot 10^{2}$
0.600	$2.2829 \cdot 10^{-3}$	2.800	$5.1612 \cdot 10^{3}$	4.900	$3.5135 \cdot 10^{2}$
0.625	$2.7948 \cdot 10^{-3}$	2.850	$8.1571 \cdot 10^{3}$	5.000	$3.1165 \cdot 10^{2}$
0.650	$3.1706 \cdot 10^{-3}$	2.900	$1.1613 \cdot 10^{4}$	5.100	$2.7350 \cdot 10^{2}$
0.675	$4.1516 \cdot 10^{-3}$	2.950	$1.2694 \cdot 10^{4}$	5.200	$2.4408 \cdot 10^{2}$
0.700	$6.0139 \cdot 10^{-3}$	3.000	$1.1394 \cdot 10^{4}$	5.300	$2.3236 \cdot 10^{2}$
0.725	$1.5860 \cdot 10^{-2}$	3.050	$9.8883 \cdot 10^{3}$	5.400	$2.3969 \cdot 10^{2}$
0.750	$2.6138 \cdot 10^{-2}$	3.100	$7.7830 \cdot 10^{3}$	5.500	$2.6504 \cdot 10^{2}$
0.775	$2.3998 \cdot 10^{-2}$	3.150	$5.3856 \cdot 10^{3}$	5.600	$3.1865 \cdot 10^{2}$
0.800	$1.9635 \cdot 10^{-2}$	3.200	$3.6285 \cdot 10^{3}$	5.700	$4.4754 \cdot 10^{2}$
0.825	$2.7722 \cdot 10^{-2}$	3.250	$2.3586 \cdot 10^{3}$	5.800	$7.1493 \cdot 10^{2}$
0.850	$4.3317 \cdot 10^{-2}$	3.300	$1.4013 \cdot 10^{3}$	5.900	$1.3248 \cdot 10^{3}$
0.875	$5.6154 \cdot 10^{-2}$	3.350	$9.7905 \cdot 10^{2}$	6.000	$2.2410 \cdot 10^{3}$

TABLE 4 (Continued)

$\lambda(\mu m)$	$\alpha(cm^{-1})$	$\lambda(\mu m)$	$\alpha(cm^{-1})$	$\lambda(\mu m)$	$\alpha(cm^{-1})$
6.100	$2.6987 \cdot 10^3$	9.800	$6.1421 \cdot 10^2$	27.000	$1.6011 \cdot 10^3$
6.200	$1.7836 \cdot 10^3$	10.000	$6.3837 \cdot 10^2$	28.000	$1.5169 \cdot 10^3$
6.300	$1.1370 \cdot 10^3$	10.500	$7.9228 \cdot 10^2$	29.000	$1.4430 \cdot 10^3$
6.400	$8.8161 \cdot 10^2$	11.000	$1.1058 \cdot 10^3$	30.000	$1.3739 \cdot 10^3$
6.500	$7.5785 \cdot 10^2$	11.500	$1.5517 \cdot 10^3$	32.000	$1.2724 \cdot 10^3$
6.600	$6.7782 \cdot 10^2$	12.000	$2.0839 \cdot 10^3$	34.000	$1.2160 \cdot 10^3$
6.700	$6.3207 \cdot 10^2$	12.500	$2.6038 \cdot 10^3$	36.000	$1.1973 \cdot 10^3$
6.800	$6.0430 \cdot 10^2$	13.000	$2.9483 \cdot 10^3$	38.000	$1.1938 \cdot 10^3$
6.900	$5.8643 \cdot 10^2$	13.500	$3.1928 \cdot 10^3$	40.000	$1.2095 \cdot 10^3$
7.000	$5.7446 \cdot 10^2$	14.000	$3.3211 \cdot 10^3$	42.000	$1.2237 \cdot 10^3$
7.100	$5.6637 \cdot 10^2$	14.500	$3.3626 \cdot 10^3$	44.000	$1.2452 \cdot 10^3$
7.200	$5.6025 \cdot 10^2$	15.000	$3.3678 \cdot 10^3$	46.000	$1.2621 \cdot 10^3$
7.300	$5.5430 \cdot 10^2$	15.500	$3.3564 \cdot 10^3$	48.000	$1.2776 \cdot 10^3$
7.400	$5.5020 \cdot 10^2$	16.000	$3.3144 \cdot 10^3$	50.000	$1.2918 \cdot 10^3$
7.500	$5.4622 \cdot 10^2$	16.500	$3.2596 \cdot 10^3$	60.000	$1.2294 \cdot 10^3$
7.600	$5.4234 \cdot 10^2$	17.000	$3.1712 \cdot 10^3$	70.000	$1.0340 \cdot 10^3$
7.700	$5.4019 \cdot 10^2$	17.500	$3.0806 \cdot 10^3$	80.000	$8.5923 \cdot 10^2$
7.800	$5.3971 \cdot 10^2$	18.000	$2.9740 \cdot 10^3$	90.000	$7.4840 \cdot 10^2$
7.900	$5.3924 \cdot 10^2$	18.500	$2.8597 \cdot 10^3$	100.000	$6.6853 \cdot 10^2$
8.000	$5.3878 \cdot 10^2$	19.000	$2.7382 \cdot 10^3$	110.000	$6.0661 \cdot 10^2$
8.200	$5.3790 \cdot 10^2$	19.500	$2.6035 \cdot 10^3$	120.000	$5.5083 \cdot 10^2$
8.400	$5.4006 \cdot 10^2$	20.000	$2.4693 \cdot 10^3$	130.000	$4.9686 \cdot 10^2$
8.600	$5.4357 \cdot 10^2$	21.000	$2.2859 \cdot 10^3$	140.000	$4.4880 \cdot 10^2$
8.800	$5.4978 \cdot 10^2$	22.000	$2.1306 \cdot 10^3$	150.000	$4.1469 \cdot 10^2$
9.000	$5.5711 \cdot 10^2$	23.000	$2.0052 \cdot 10^3$	160.000	$3.8956 \cdot 10^2$
9.200	$5.6685 \cdot 10^2$	24.000	$1.8902 \cdot 10^3$	180.000	$3.4837 \cdot 10^2$
9.400	$5.7886 \cdot 10^2$	25.000	$1.7895 \cdot 10^3$	190.000	$3.3136 \cdot 10^2$
9.600	$5.9429 \cdot 10^2$	26.000	$1.6916 \cdot 10^3$	200.000	$3.1667 \cdot 10^2$

In the discussion to follow, water content shall be expressed in terms of g/cm^3 and represented by w. This parameter varies with the type of tissue, and of course with water losses at elevated temperatures. Values of w are reported by Spells (20) as 0.20 and 0.75 g/cm^3 for fat and muscle, respectively. Our measurements for dermal tissues indicate a w value of 0.80 g/cm^3. Values for the epidermis will vary widely according to the relative humidity, temperature of the skin, and most importantly with whether or not sweat is present. If sweat is absent, we shall assume that w increases linearly with depth starting with a value of 0.2 g/cm^3 at the surface of the skin and ending with a value of 0.8 g/cm^3 at the epidermal/dermal interface. If sweat is present, we shall consider a w value of 1.05 g/cm^3 at the surface of epidermis which decreases linearly to 0.8 g/cm^3 at the interface with the dermis.

Specific Heat--Awbery and Griffiths (1) have measured the specific heat of meat containing various amounts of water. Figure 2 of their paper indicates that the specific heat C varies linearly with water content w divided by skin density ρ as follows

$$C = 0.37 + 0.63(w/\rho) \qquad (4)$$

When w and ρ are set equal to one, equation 4 approximates the specific heat of water.

In equation 4, the value 0.37 represents the specific heat of the non-water constituents. To check equation 4 pig fat was oven dried and its specific heat measured as 0.39 ± 0.03 cal/g-°C. Within the estimated experimental error, this measurement agrees with the value 0.37 given by equation 4.

Thermal Conductivity--Spells (20) has plotted the thermal conductivities of a wide variety of biological media as a function of water content. This includes muscle, fat, kidney tissues, blood, liver, milk, eggs, etc. The result shows that a linear relationship exists between thermal conductivity K and water content w as described below.

$$K = (0.133 + 1.36\, w/\rho)10^{-3} \text{ cal/cm-sec-°C}. \qquad (5)$$

If one substitutes a value of 1 for w/ρ, equation 5 predicts a conductivity of $1.49 \cdot 10^{-3}$ cal/cm-sec-°C which is in substantial agreement with the conductivity $1.53 \cdot 10^{-3}$ for pure water at normal body temperature.

For a typical w/: value of 0.8 for skin, equation 5 indicates a thermal conductivity of $1.22 \cdot 10^{-3}$ cal/cm-sec-°C. This value may be compared with values ranging from $0.85 \cdot 10^{-3}$ to $1.60 \cdot 10^{-3}$ found in the literature (5,25). The relatively large variation of conductivity reported above could be due to differences of water content.

Density--Densities of skin, fat, and muscle were calculated using the weight and volume measurements of Cooper et al. (4) for each of three media. Each media involved five sets of measurements and yielded the mean densities presented below

$$\text{density of skin} = 1.03 \text{ g/cm}^3 \tag{6}$$

$$\text{density of fat} = 0.98 \text{ g/cm} \tag{7}$$

$$\text{density of muscle} = 1.01 \text{ g/cm}^3 \tag{8}$$

Here one must recognize that the density for skin represents a mean value for the entire skin which consists predominantly of dermal tissues. The density given by equation 6 should not be applied to the epidermis unless it is saturated with moisture.

The above brings us to the problem of computing densities in terms of varying water content. Here we shall assume the volume remains invariant with changes in water content. Proceeding upon this basis the density ρ of skin, fat, or muscle is given by

$$\rho = s + w \tag{9}$$

where s represents the mass of all nonaqueous ingredients per cm^3.

In equation 9, w represents the primary variable in that organic materials require temperatures well above boiling water for distillation or decomposition. The variable s may be estimated for various tissues using the densities presented by equations 6 through 8 along with the w values presented at the beginning of this section.

Blood Flow

Of all the parameters, blood flow is the most difficult to quantify in that it varies from individual to individual as well as with skin location and temperature. With inclined resting human beings, Cooper et al. (4) found that blood flow can range from 0 to 0.0118 cm^3/cm^3 of muscle/sec at normal environmental temperatures. At an environmental temperature of 35°C, the results of Hardy and Solderstom (9) and Behnke and Willman (2) indicate blood flows in the forearm skin of 0.00025 and 0.00020 cm^3/cm^3 of skin/sec respectively. In spite of the elevated environmental temperature, these flows are well within the range of values found by Cooper et al. (4).

Senay et al. (19) report increases of blood flow brought about by temperature changes. In raising the forearm skin from 32°C to 37°C, blood flows were found to increase by 0.000027 cm^3/cm^3 of forearm skin/sec, and increase by 0.000100 cm^3/cm^3 of calf skin/sec. They indicate that vasodilation occurred at 31.4°C and 33.7°C for skin at the calf and forearm, respectively. While these blood flow changes are significant with respect to the flow rates determined from the results of Hardy and Solderstom (9) and Behnke and Willman (2), they are very small compared to the range of possible blood flows cited previously from Cooper et al. (4). In this regard no data could be found describing the effects of local heating upon increased blood flow.

Until such data are available, we suggest use of the highest values found for skin and muscle by Cooper et al. (4). Such values will not appreciably affect skin temperatures unless the exposures are of the order of 1 sec or longer in duration.

Heat-Transfer Coefficients

Surface of Skin--This section is concerned with rates of heat loss from skin surfaces. Such fluxes equal the product of a heat-transfer coefficient and the difference between the temperatures of the surface of the skin and the surrounding air. It depends upon

- air motion
- surface orientation, moisture, and temperature
- relative humidity of surrounding air.

Here we have experimentally determined the heat-transfer coefficient associated with wet and dry vertical surfaces exposed to still air at 22°C with a relative humidity of 50%. These conditions are considered typical of those likely to be encountered. Dependence of the heat-transfer coefficient on temperature is of minor importance and hence will be neglected.

In the experiments, an electrical heater was placed in a 10-cm diameter, 2-cm-thick aluminum disk whose sides and back face were insulated with 2 cm of styrofoam. The test face was left bare to simulate dry skin or covered with wet tissue paper to simulate wet skin. Temperatures within the aluminum disk and styrofoam were measured by means of thermocouples.

The rate of heating was adjusted until the aluminum disk reached 70°C. Heat fluxes leaving the test face were determined by first calculating the relatively small heat losses through the styrofoam. These losses were then subtracted from the measured rate of heating, and divided by the product of face area and the temperature difference between the disk and surrounding air. Resultant heat-transfer coefficients h_e for dry and wet surfaces are as follows:

$$h_e = \begin{cases} 2\cdot 10^{-4} \text{ cal/cm}^2\text{-sec-°C, dry surfaces} \\ 7\cdot 10^{-4} \text{ cal/cm}^2\text{-sec-°C, wet surfaces} \end{cases} \qquad (10)$$

The above value for dry surfaces contrasts well with the value $1.5\cdot 10^{-4}$ cal/cm^2-sec-°C found in ref. 26.

Because the epidermis is usually quite dry, we recommend use of the coefficient for dry surfaces unless sweat is present.

If water commences to boil, tissues will rapidly lose their water. Rates at which heat is expended in transforming water into steam were roughly 100 times larger than heat fluxes due to natural convection/reradiation. Thus very little is gained by altering the coefficient as the skin surface dries.

Steam Blisters--Heat is transferred across steam blisters by all modes of heat transfer, namely conduction, radiation, and convection. Rates of heat transfer will be described by the product of a heat-transfer coefficient and the temperature difference across blisters. Of all the parameters, the coefficient is the most difficult to quantify in view of variations in blisters.

The section "Criterion for Fifth-degree Burns" estimates the heat-transfer coefficient as $6\cdot 10^{-3}$ cal/cm^2-sec-°C. This coefficient will be considered constant independent of temperature, and it is the factor by which temperature differences across the blisters are multiplied to determine heat fluxes crossing the water vapor within the blister. Much of this heat transfer is by thermal conduction and to a lesser extent by thermal radiation.

Damage/Burn Predictions

Extent of Thermal Damage--Extent of irreversible damage is predicted using the same expression used by the eye models (23). In this regard thermal damage Ω is computed as follows:

$$\Omega = \int_0^\infty A_1 \exp -A_2/v_a(t)\ dt \qquad (11)$$

where A_1 = step function of v_a, 1/sec

A_2 = step function of v_a, K

v_a = temperature in °K

t = time in sec.

This expression was originally proposed by Henriques (11) and subsequently used by a number of other investigators such as Stoll and Greene (21). Values for A_1 and A_2 are presented below (22):

$$\left.\begin{array}{l} A_1 = 4.322\cdot 10^{64}/\text{sec} \\ A_2 = 50{,}000°\text{K} \end{array}\right\} 317 \le v_a \le 323°\text{K} \qquad (12)$$

$$\left.\begin{array}{l} A_1 = 9.389\cdot 10^{104}/\text{sec} \\ A_2 = 80{,}000°\text{K} \end{array}\right\} 323 \le v_a \le 333°\text{K} \qquad (13)$$

Below 317°K A_1 is zero. In this regard we were not able to evaluate A_1 and A_2 values beyond 333°K due to the absence of high temperatures at burn thresholds. Higher temperatures will be achieved only with very short pulses--of the order of 1.10^{-5} sec or less.

Degree of Burn--Burns range from first degree to fifth degree. Visually these burns are characterized as follows:

first-degree burn --- red

second-degree burn --- red with white spots

third-degree burn --- entirely white

fourth-degree burn --- steam blister

fifth-degree burn --- char.

Characterizing burns in the above manner provides a rough estimate of the damage. However, it is not indicative of the depths to which tissues are irreversibly damaged. For example, very intense short-duration heating can char the surface with only shallow dermal damage. On the other hand, low intensity long-duration heating can entirely destroy the dermis with no charring.

Criteria for each of the five degrees of burn were obtained by examining computed peak temperatures and Ω values at particular burn radii. These criteria are presented below:

first-degree burns --- $\Omega = 0.1$ (assumed)

second-degree burns --- $\Omega = 1.0$

third-degree burns --- $\Omega = 10,000$

fourth-degree burns --- 131°C at base of epidermis

fifth-degree burns --- 400°C at exterior surface of epidermis

SKIN MODEL

As noted earlier, the skin model utilizes an implicit-explicit finite-difference method (14,23) to predict transient temperatures produced in skin by lasers. Thermal conduction is treated using polar coordinates.

In this program the method cited above was upgraded to account for:

- coded pulses (variable pulse durations and power)
- temporal property changes (thermal and optical)
- steam blisters
- heat losses due to the generation of steam
- interception of radiation by hair follicles
- variable blood flow rates with respect to depth.

In addition, criteria were introduced for predicting the degree of burn. Means for predicting the extent of irreversible thermal damage remain the same as that developed for skin (22) and used for the eye (23).

This section is concerned with describing essential features of the model. Details are presented in Appendixes A, B, and C. Appendix A presents the finite-difference representation of the heat conduction problem along with its solution; Appendix B describes means by which long pulse trains are treated to conserve computational time; and Appendix C discusses functional details of the code.

Laser Exposures

The model is capable of handling any laser exposure involving radially symmetric beams that are perpendicular to the surface of the skin. Beam profiles may have any symmetric shape while the laser may have any wavelength and be continuous or pulsed. Laser powers are considered constant during each pulse.

Two types of pulse trains may be treated by the code. The first is noncoded pulses in which all the pulses are identical. The second is coded pulses in which the pulses vary in power and duration. Times between successive coded pulses may vary from 0 to any value desired. Using this provision one can consider laser exposures with time-dependent power of any description.

Grid

A nonuniform grid is used to conserve computation time Within regions of pronounced heat deposition, grid points are spaced at regular small intervals as shown in Figure 8. Beyond this region, the grid spaces are progressively increased as follows:

$$\Delta z_i = C_1 z_{i-1} \tag{14}$$

$$\Delta r_j = C_2 r_{j-1} \tag{15}$$

The constants C_1 and C_2 are chosen large enough so that remote grid points, such as r_{N+1}, z_{M+1}, do not sense any heating whatsoever.

The only exception to the grid shown in Figure 8 is when a hair follicle is to be included. The follicle is located on the axis and occupies the first radial increment Δr_1. Subsequent radial increments are uniform and then expanded as per Figure 8. Axial increments are selected so that the follicle occupies one of the Δz increments. To achieve this end the axial grid is expanded for several increments as shown in Figure 8 and then contracted to the diameter of the follicle. Beyond the follicle the expansion is resumed. Further details are presented in Appendix C.

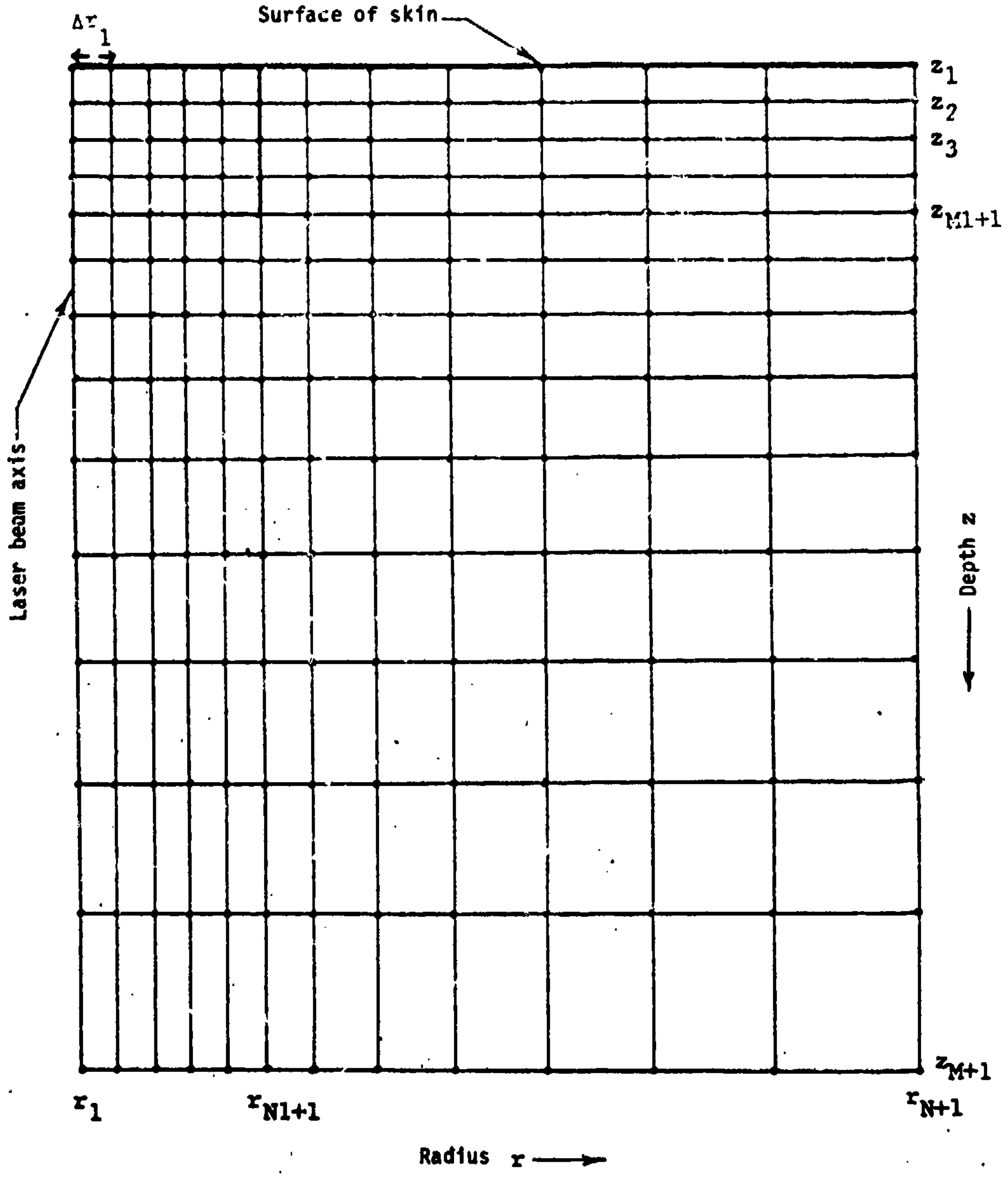


Figure 8. Radial and axial grid points and increments.

Assignment of Properties and Energy Deposition Rates

Thermal properties, absorption coefficients, densities, water content, and blood flow rates are varied with depth in a stepwise fashion according to the thicknesses of the epidermis, dermis, and any sweat layer. The steps may be made as small as the data allow.

Energy deposition rates are calculated by first assessing the beam intensities at each of the grid points illustrated in Figure 8. These intensities are computed using Beer's Law at depths z_i beneath Z_{L-1} as follows:

$$q(r_j,z_i) = (1-H)(1-\xi)q_o(r_j)\exp-(\alpha_o Z_o+\alpha_1(Z_1-Z_o) + \ldots\alpha_L(z_i-Z_{L-1})) \quad (16)$$

where $q(r_j,z_i)$ = intensity at grid point r_j, z_i, cal/cm^2-sec

H = fraction of radiant energy intercepted by hairs, dimensionless

ξ = reflectance, dimensionless

$q_o(r_j)$ = incident beam intensity at radius r_j, cal/cm^2-sec

$\alpha_o,\alpha_1\ldots\alpha_L$ = absorption coefficients of tissues between depths 0 to Z_o, Z_o to Z_1, ..., Z_{L-1} to Z_L, respectively, 1/cm

Rates of energy deposition $\bar{q}(r_j,z_i)$ are computed as follows

$$\bar{q}(r_j,z_i) = \frac{q(r_j,z_{i-1}) - q(r_j,z_{i+1})}{z_{i+1}-z_{i-1}} \quad (17)$$

When a hair follicle is present at r_j,z_i then

$$\bar{q}(r_j,z_i) = q(r_j,z_i)/(z_i-z_{i+1}) \quad (18)$$

Heat Transfer

Heat transfer within the skin and subcutaneous tissues is computed using finite-difference approximations of the heat conduction equation (modified) for heat deposition and blood flow. This equation is presented below:

$$\rho C\frac{\partial v}{\partial t} = \bar{q} + \frac{K}{r}\frac{\partial v}{\partial r} + \frac{\partial}{\partial r}\left(K\frac{\partial v}{\partial r}\right) + \frac{\partial}{\partial z}\left(K\frac{\partial v}{\partial z}\right) - \bar{B}C_b v - \bar{\bar{q}} \qquad (19)$$

where ρ = tissue density, g/cm^3

C = specific heat of tissues, cal/g-°C

v = temperature, °C

t = time, sec

$\bar{q}$ = rate of heat deposition, cal/cm^3-sec

K = thermal conductivity, cal/cm-sec°C

r = radius, cm

z = depth, cm

$\bar{B}$ = rate of blood flow, g/cm^3-sec

C_b = specific heat of blood, cal/g-°C

$\bar{\bar{q}}$ = rate of heat loss in transforming water into steam, cal/cm^3-sec

Initially, the thermal properties and blood flow rates vary only with depth. Thereafter, the densities ρ, specific heats C and thermal conductivities K are altered with respect to radius and depth as water is transformed into steam. Expressions are presented in the section "Thermal Properties of Skin" for the thermal conductivity and specific heats as a function of water content w divided by density ρ.

In equation 19, the blood flow $\bar{B}$ is considered to enter capillaries through large blood vessels at the initial skin temperature. Thereafter the blood assumes the temperature of the tissues before leaving through other major blood vessels. In this respect the blood acts solely as a heat sink. Heat transport from one location to another is neglected in that it is of minor importance compared to other heat losses, namely by thermal conduction and by blood acting as a heat sink.

Initially the skin and subcutaneous tissues are assumed to be at a uniform temperature. Biological heating is neglected. To simplify the temperature calculations, all tissue temperatures are given as temperature differences with respect to the temperature v_e of the surrounding air. Ambient air temperatures may be higher or lower than the initial temperature of the skin.

Rates of heat loss from the surface of the skin are described by

$$-K\frac{\partial v}{\partial r} = h_e v, \quad z=0, \quad t > 0 \qquad (20)$$

Due to radial symmetry heat does not flow across the axis. Thus

$$K\frac{\partial v}{\partial r} = 0, \; r=0, \; t \geq 0 \tag{21}$$

At distances far away from the regions of energy deposition, temperatures must approach their initial value $v_o - v_e$. This is expressed by

$$v \to v_o - v_e \text{ as } r \text{ and/or } z \to \infty \tag{22}$$

Once a steam blister forms, heat fluxes to the underlying tissues are reduced by the film of water vapor generated within the blister. Neglecting the heat capacity of the water vapor within the blister, the heat fluxes leaving the blister are identical to those entering the underlying tissue. Mathematically this is described as follows:

$$-K\frac{\partial v}{\partial z}\Big|_{Z_w-\delta} = -K\frac{\partial v}{\partial z}\Big|_{Z_w+\delta} = h_w\left(v\big|_{Z_w-\delta} - v\big|_{Z_w+\delta}\right) \tag{23}$$

where Z_w = depth at which blister forms (namely that of the epidermal-dermal interface), cm

δ = an incrementally small displacement from Z_w, cm

h_w = heat-transfer coefficient across blister, cal/cm^2-sec-°C

Water within tissues beneath the blister is assumed to be contained following blister formation. This, of course, raised the possibility of superheated water along with elevated pressures within tissues beneath the blister. No provisions have been made for blister rupture.

Heat losses due to the generation of steam are accounted for by introducing positive values for $\bar{\bar{q}}$ in equation 19. Such values are introduced for grid points within the epidermis wherein temperatures reach that of boiling water during periods while water is present. Other grid points have $\bar{\bar{q}}$ values of zero.

Values for $\bar{\bar{q}}$ are adjusted by trial and error until the temperatures at the appropriate grid points approximate that of boiling water. Usually four trials are required. Following each trial, the $\bar{\bar{q}}$ values are revised based upon calculated temperatures using the previous $\bar{\bar{q}}$ values. After the last trial, the water content within the tissues is adjusted according to the loss of water. Once tissues lose all their water, temperatures are allowed to increase without bounds.

Thermal Damage Predictions

Tissues are considered irreversibly damaged when the value Ω of equation 11 equals or exceeds 1. In this equation rates of damage increase exponentially with respect to temperature. In the model rates of damage are computed during selected time steps. Cumulative damage is predicted by multiplying these rates by the associated time steps and summing the damage over time.

Degrees of burn are predicted as described in the section "Damage/Burn Predictions." Here peak Ω values are used to describe the occurrence of first-, second-, and third-degree burns. Fourth-degree burns are predicted when a steam blister forms and fifth-degree burns when the peak temperature is adequate to char tissues.

PIG EXPERIMENTS

This section describes exposure of 20 pigs (30 burn sites per pig) to a CO_2 and ruby laser. Included are discussions of:

- optical and animal-handling procedures
- histological procedures and results
- criteria describing the
  - formation of steam blisters, and
  - degree of burns.
- comparison of radial and axial extent of irreversible damage with model predictions.

The CO_2 laser was continuous with a nominal power of 5 watts. The ruby laser provided single pulses of 50- or 500-μsec duration with a maximum nominal energy of 25 joules. Both lasers functioned somewhat below their nominal power/energy levels. Beam powers were measured by means of a power meter at various times during the experiments. In each set of experiments, the power remained reasonably stable as will be shown later in this section.

Immediately before each exposure, skin temperatures were stabilized at 37°C. This was achieved by contacting the skin with a warm aluminum disk held at 37°C for one-half minute.

Various aspects of the CO_2 experiments are shown in Figure 9. Included are the test setup as well as pictures of the resultant burns. The scale in the photograph at the lower left is in mm; it shows a typical fifth-degree burn as evidenced by black char at the center of the burn site. A third-degree burn is shown at the lower right as evidenced by the relatively large white circular area. Around this and all other white areas is a red ring.

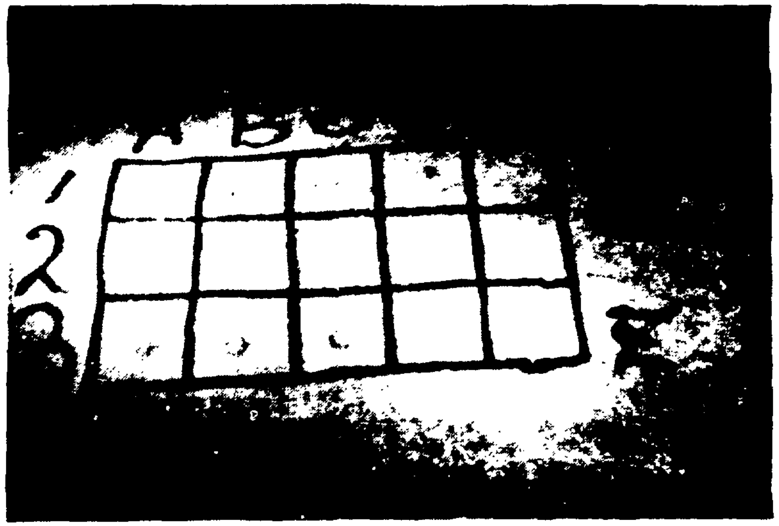
The photograph at the upper right shows burns created by exposures to the CO_2 laser with a power of 1.55 watts and a beam radius at the $1/e^2$ points of 0.710 cm. Each column represents a different exposure time. Burns in columns A, B, C, D, and E were produced by 10-, 15-, 20-, 7.5- and 5-sec duration exposures to the CO_2 laser. Burns in columns A, B, and C were white surrounded by a red ring while those in column E were entirely red. Burns in column D were predominantly red with a barely perceptible white spot at the center.

In the remainder of this section we shall discuss the experimental procedures, compare model predictions with those found experimentally, and interpret the data in regard to heat-transfer coefficients and burn criteria.

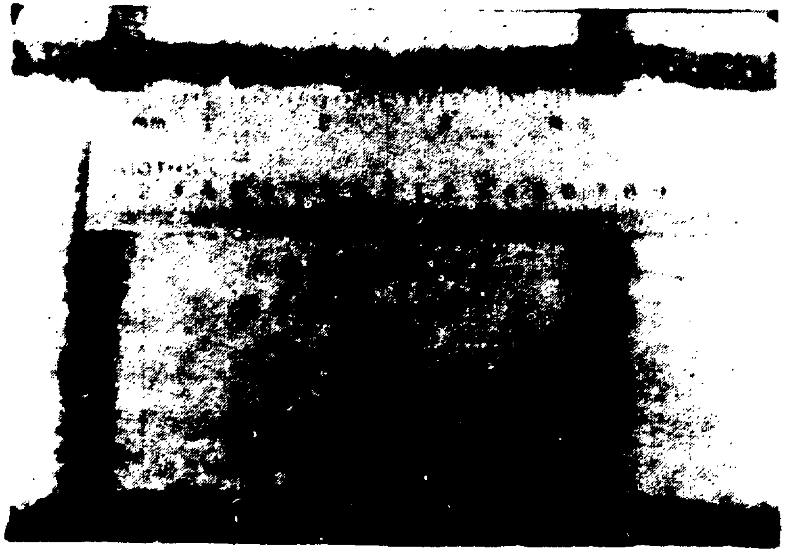
Optical Setups and Measurements

CW CO_2 Laser--To provide reproducible exposures care was taken so that all burn sites were located at a fixed distance of 150 cm from the laser. The normal beam divergence produced a spot size of approximately 0.73 cm measured at the $1/e^2$ points. The optical arrangement is shown in Figure 10. Two folding mirrors are used. The first mirror is used to change the beam direction in the horizontal plane, and the second mirror is used to direct the beam downward through an aperture onto the animal. The aperture is an adjustable iris so that all or any portion of the beam may be used. Further increases in beam diameter may be made by replacing the first mirror with a convex mirror of long focal length. Exposure times are controlled by an electromechanical shutter driven by an electronic interval timer.

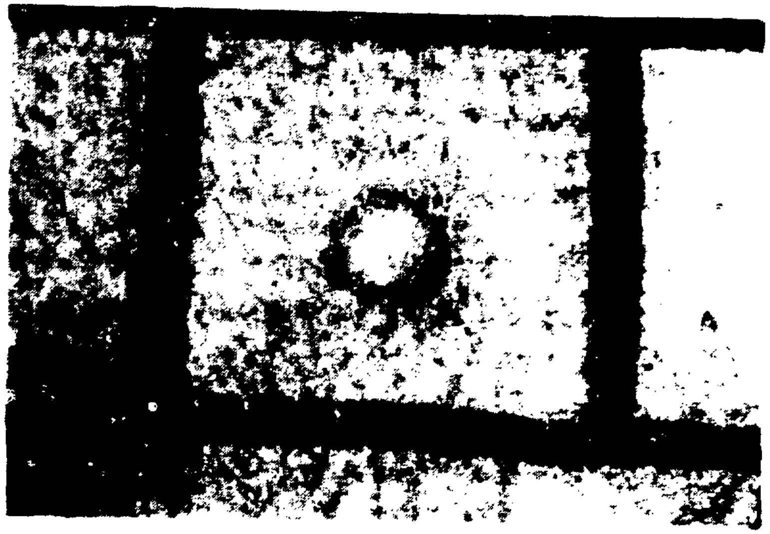
Test setup for CO_2 laser exposures



Grid work used to mark burn sites, C3 burn site shown below



20-sec exposure to CO_2 laser
(Power = 1.55 watts; beam radius = 0.383 cm)



20-sec exposure to CO_2 laser
(Power = 1.53 watts; beam radius = 0.710 cm)

Figure 9. CO_2 laser setup and resultant burns.

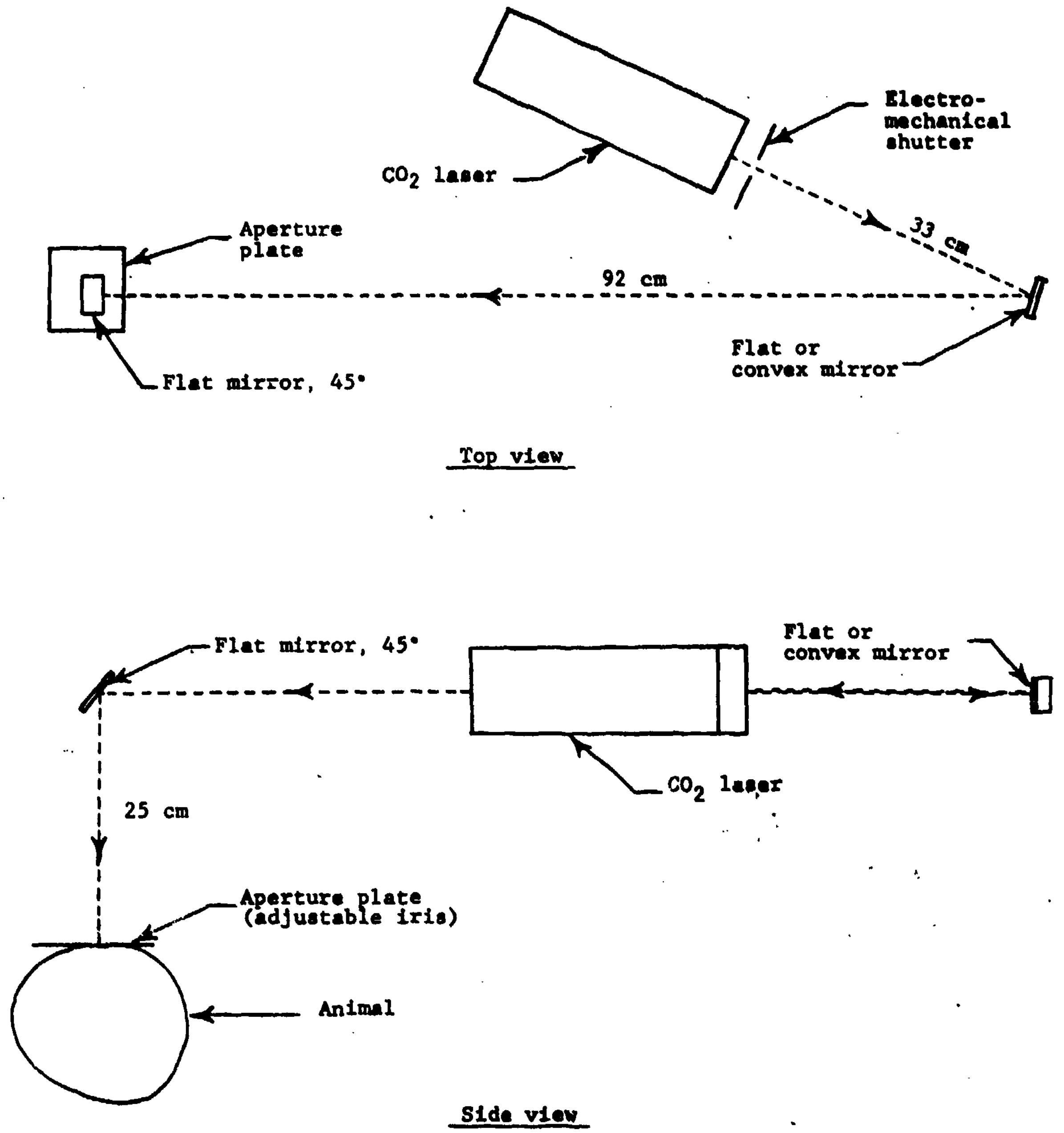


Figure 10. Optical system for controlling animal exposure (CO_2 laser).

The entire optical system described above, along with laser power supply, is mounted on a portable cart to enable the system to be moved to the animal facility.

Beam profiles for our CW CO_2 laser are presented in Figures 11 and 12. Figure 11 presents the profiles of the beam as it leaves the laser, while Figure 12 presents the profiles after the beam is expanded by a convex mirror. The two profiles represent the profiles in two perpendicular directions. These profiles were obtained by traversing a 0.030-cm pinhole across the beam in steps of 0.064-cm, and measuring the power passing through the pinhole. The mean deviation of the power measurements from the curves of Figures 11 and 12 was 0.05 milliwatts.

All profiles shown in Figures 11 and 12 are essentially gaussian in shape. Notice, however, that the beams are not quite circular--deviating in radius by about 5% in the two directions. In this regard we shall use the mean value of the two radii cited in each of the figures.

Ruby Laser--The ruby laser operates in two modes at a wavelength of 0.6943 μm. The first mode provides 25 joules of energy over a pulse duration of 500 μsec. The second mode provides a variable output of 0 to 10 joules with a pulse duration of 50 μsec. Repetition rates may be varied provided there is a minimum of 60 sec between pulses.

The setup used to expose pigs to the ruby laser is shown in Figure 13. In essence the beam passed through a prism and a Galilean telescope before being diverted downward through a second prism. Measurements of the beam profile were made using the same procedure as that described for the CO_2 laser beam. Results are shown in Figure 14.

Animal Procedure, Autopsy, Histological Procedure, and Results

Twenty pigs each weighing approximately 27 kg were used in the experiments. They arrived at the animal facility at least 1 to 2 days before being used in the experiments. Food and water were withheld from the animals the night before exposing them to the lasers.

Three to four pigs were exposed each day. The pigs were first tranquilized with Sernylan (0.5 - 1.0 mg/kg), making them groggy and allowing administration of pentobarbital through a catheter placed in their ear vein. Pentobarbital was infused as needed--based on the response of the animal to external stimuli. Although it was originally planned to

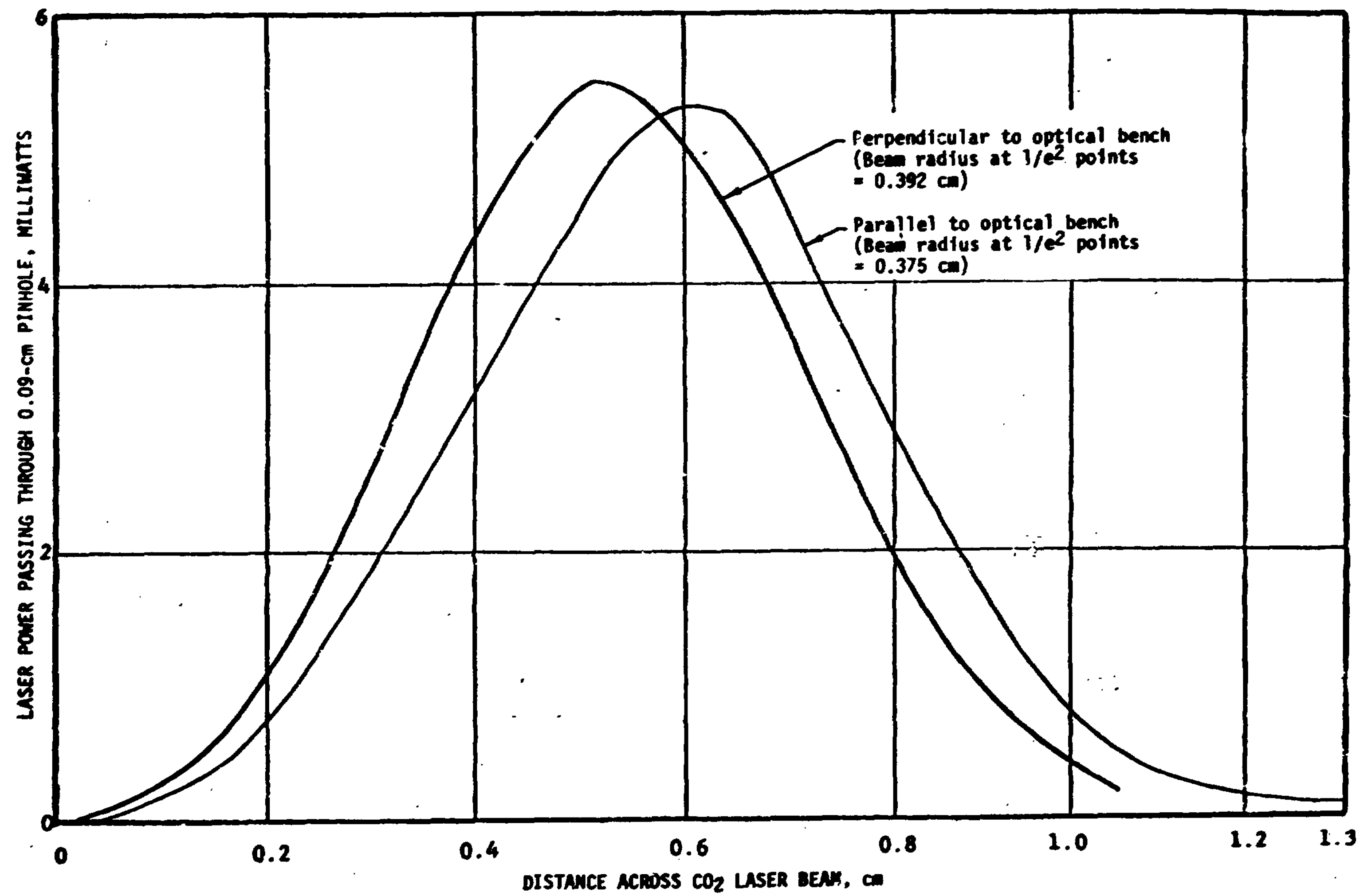


Figure 11. Profiles of unexpanded CO_2 laser beam (2 directions). Both curves are "eyeball" fits to the data.

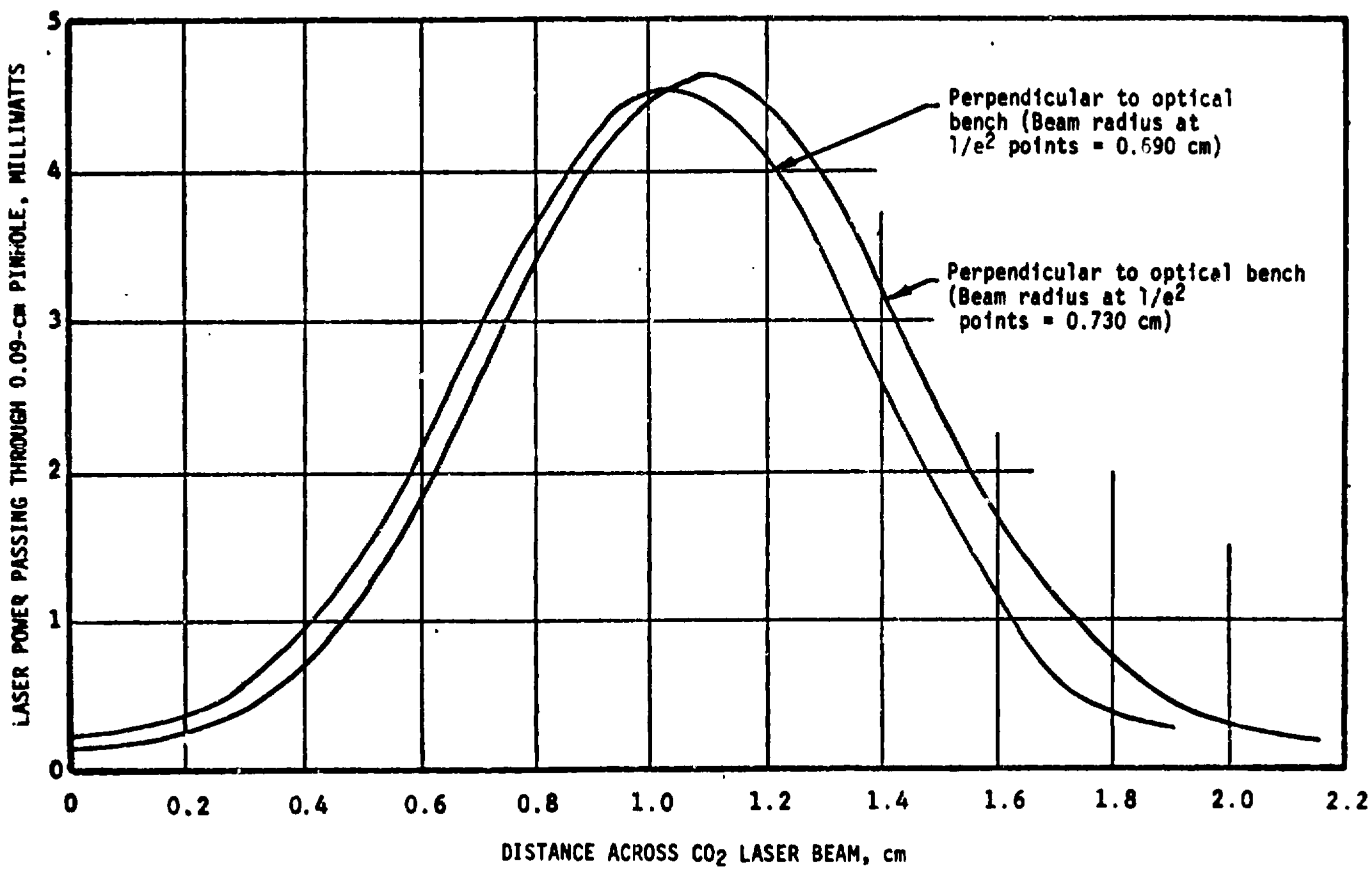


Figure 12. Profiles of expanded CO_2 laser beam (2 directions). Both curves are "eyeball" fits to the data.

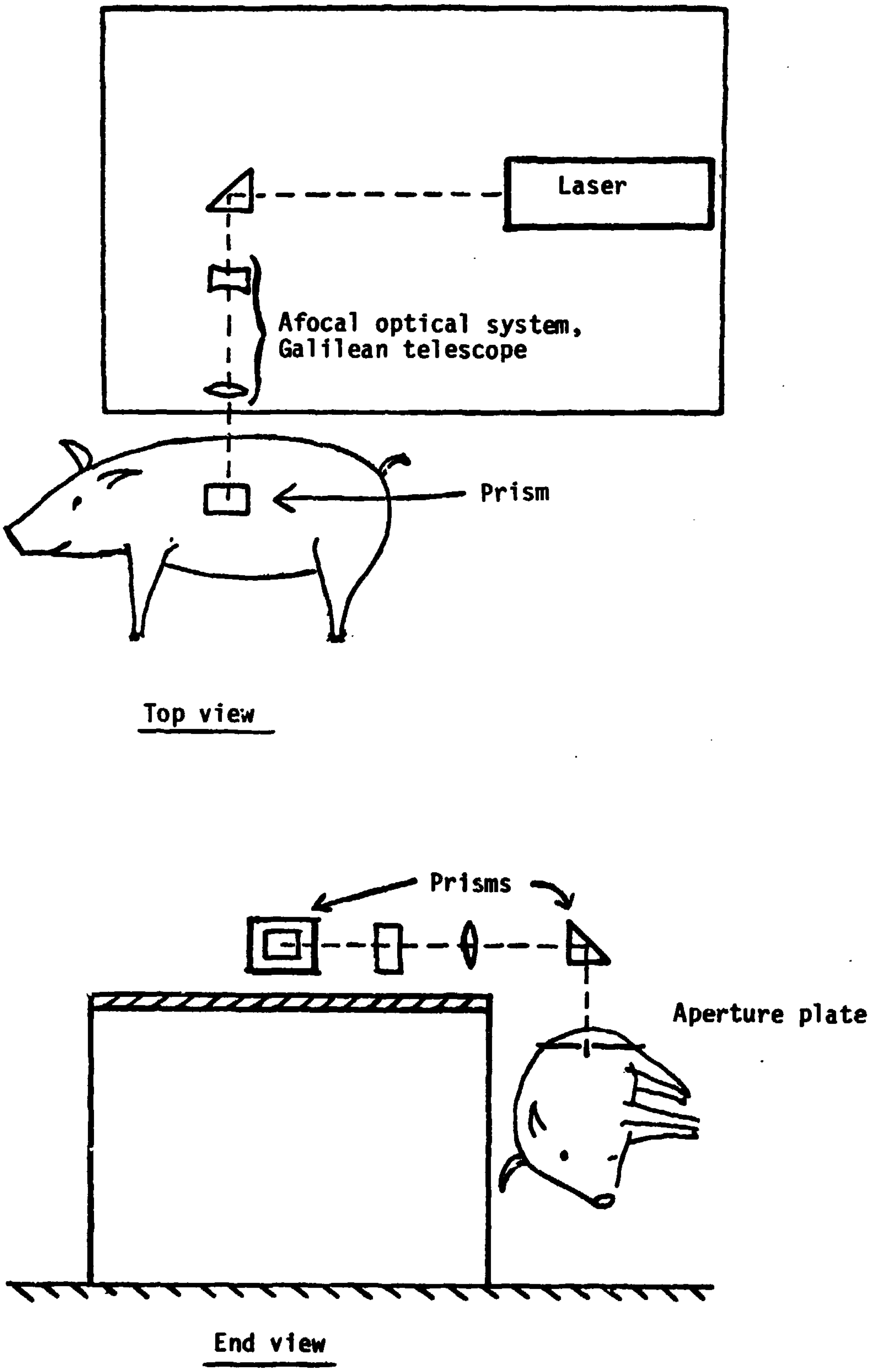


Figure 13. Optical system for ruby laser.

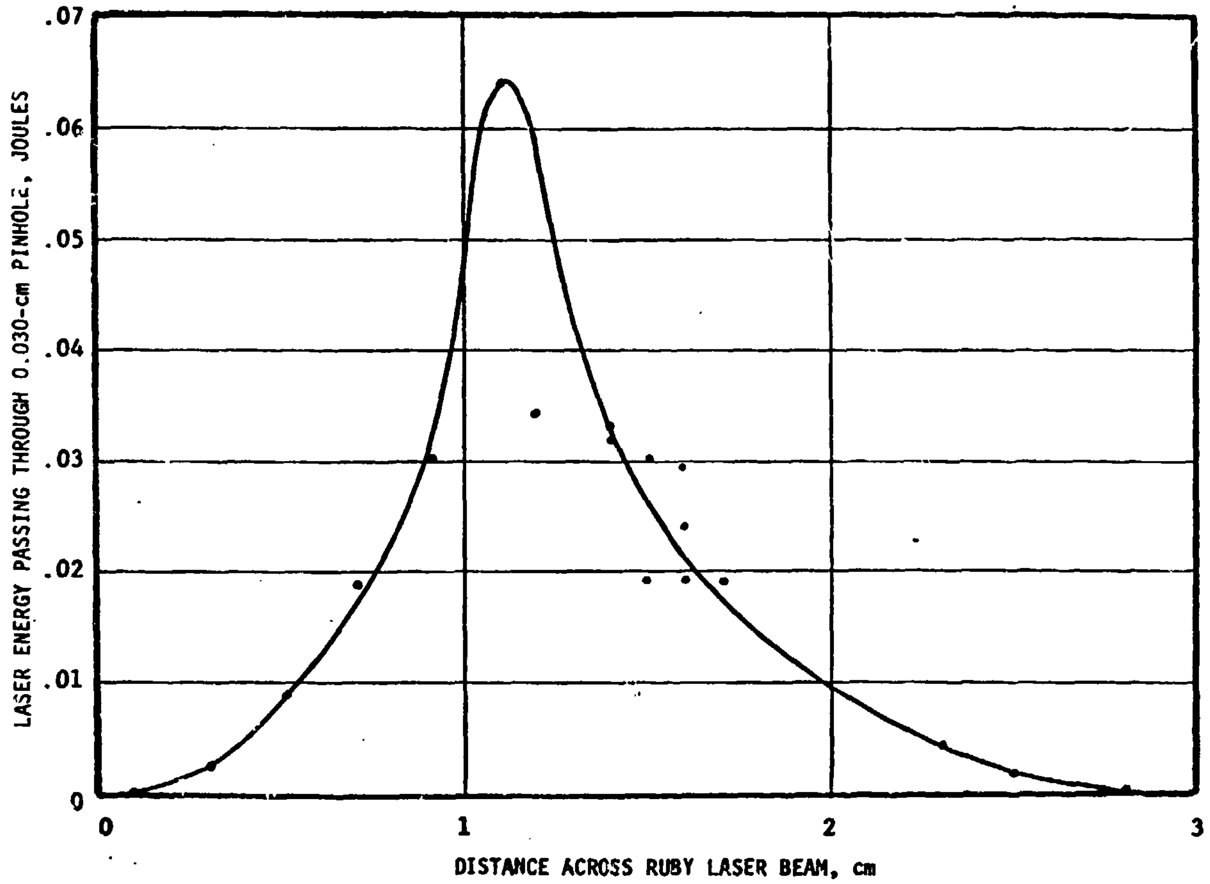


Figure 14. Profile of normal ruby laser beam. Curve is "eyeball" fit to the data.

use Sernylan for the entire procedure, it was difficult to keep the animals quiet with only this agent. Pentobarbital proved to be an excellent anesthetic and none of the animals died during its use. Care had to be taken, however, since it is easy to overdose the animals with pentobarbital. One animal showed respiratory arrest, but immediate administration of artificial respiration as well as the respiratory stimulant Dopram revived the animal.

Once the pig was sufficiently anesthetized, the animal's flank was shaved with an electric razor. Extreme care was taken since this can produce some erythema or even abrasions. The hair remover (Nair) was subsequently applied for approximately 10-15 minutes after which it was rinsed off with warm water. Two applications of Nair were usually necessary to remove all the hair and to produce a smooth, abrasion-free skin.

Fifteen areas were marked and numbered for reference purposes with indelible ink on each side of the animal. All burn sites were completely white. These areas were varied in size, depending on the laser exposure, to assist in detecting barely visible burns at autopsy.

Deep anesthesia was required when the animals were actually exposed to the lasers since they have a tendency to flinch their skin. Just before exposure, pentobarbital was administered until the second or third (surgical) stage of anesthesia was obtained. After exposure to the laser beams, the pigs were kept overnight in individual cages to prevent the exposure sites from getting dirty and other pigs from biting and licking at the burn sites.

Twenty-four hours after the laser treatment, the pigs were euthanized. First they were tranquilized with Sernylan and then received an intravenous administration of Euthobarb. The pigs were immediately autopsied. Deep cuts were made some distance from the edges of the burn sites and went all the way through the fat to the abdominal muscle layers. The tissues were placed in plastic bags containing Bouin's fixative and delivered to the pathologist for sectioning and observation.

Once these techniques were developed, the entire procedure became very routine and no difficulties were encountered.

Histology Thicknesses/Depths of Skin and Other Media--From the outside inwards, the skin consists of a thin epidermis that is composed of several layers of cells and a thicker dermis that is composed of connective tissue. Underneath the dermis lies a layer of fat. Glands, hair follicles, and small blood vessels are also present in the skin.

Thicknesses of significant normal structures of pig skin are listed below:

Epithelium or epidermis:	0.0081 - 0.0161 cm (mean = 0.0121 cm)
Dermis:	0.1078 - 0.2479 cm (mean = 0.1779 cm)

Capillaries were located at depths ranging from 0.0135 to 0.0216 cm while glands or hair follicles ranged in depths from 0.1617 to 0.2695 cm (mean = 0.2156 cm). All of the above measurements were corrected for tissue shrinkage.

Qualitative Effects of Excessive Heat--When the skin is damaged by lasers, cells will die. Cell death or damage may be indicated by a complete absence of the cell or more subtle changes in the appearance or staining reaction of the cell nucleus or cytoplasm. Concomitant with cell death is normally an influx of white blood cells attempting to remove the dead and damaged cells. The extent of damage caused by the laser beam is therefore indicated by the depth and radius in the skin that dead cells can be found as well as the presence of white blood cells.

Depending on the characteristics of the laser beam, the damage varies in depth but occasionally goes all the way into the fat layer. Some cells are more sensitive to laser damage than others. For instance, cells lining blood vessels and glands are particularly susceptible, whereas fat cells are less susceptible than other cells of the dermis. Thus, it is possible to find areas, particularly in the fat and also in the dermis, where the blood vessels and glandular cells show damage but the surrounding tissue cells do not. A sharp line of demarcation between damaged and undamaged tissue is therefore not present. In the measurements, the furthest point was taken at which any cell damage could be observed.

Histology Procedures and Observations--A total of 582 of the 600 burn sites were submitted for histological examination. The skin samples were received fixed in Bouin's fixative. They remained in fixative 1-3 days and were then washed in three changes of 50% alcohol to remove the fixative. The tissue was trimmed for processing by cutting through the center of the burn site, embedding one half with the lesion down to insure sectioning through the center of the lesions for accurate measurement. The other half was stored for future reference. The tissue was then dehydrated in alcohol, embedded in paraffin, sectioned at 6 microns and stained with hematoxylin and eosin. Four to six sections were cut from the face of the paraffin block to obtain a section through the lesion center.

The tissues were then evaluated by histologic examination and the radius and depth of the thermal damage were determined. The injured tissue is described as follows. There was coagulative necrosis of varying depth at the burn site with loss of epithelium covering some of the more severe burns. The pattern of necrosis was roughly the shape of a flattened cone. Epithelial cells had pyknotic or shrunken dense nuclei or occasionally fragmented nuclei. The cytoplasm lost its basophilia and was more eosinophilic than adjacent normal epithelium. Similar changes were seen in cells lining the hair shafts. Necrotic fibroblasts were detected by the presence of pyknotic nuclei; cytoplasm was too sparse to be visible. The upper layers of collagen were blue in color and the filamentous structure was obscured. Deeper in the lesion, the collagen retained its structure but was altered in color. Deeper there was an indistinct region of questionable change although cellular elements at this level were necrotic. There was mild and variable polymorphonuclear infiltration at the deep edge of the lesion.

Some cellular elements were more sensitive to injury than others. They were necrotic at a greater depth than resistant tissues. Thus there was no sharp edge to the burn lesion. The blood vessel endothelium and supporting tissue are most sensitive as well as the glandular epithelium. Fat tissue and fibroblasts are less sensitive than the above elements. Glands and blood vessels well within the panniculus adiposus were necrotic in some animals but the surrounding fat was normal.

The depth of the lesion was measured to the deepest point of observed damage. The radius was very precise in its outline as the surface epithelium presented a sharp junction of normal and injured cells. When the epithelium was lost from the surface, the depth measurement included an estimate of its thickness.

<u>Dimensional Changes of Skin Specimens</u>--Skin specimens contract upon being excised from the animals. Further contraction was observed in preparing the specimens for histologic measurements. No dimensional changes occurred between exposing and sacrificing the animals.

Skin contraction caused by excising was quantified by comparing photographs of the burn sites before and immediately after excising. From these photographs the following results were obtained:

- Normal undamaged skin contracts linearly along the surface by $12.0 \pm 3.2\%$. This figure applies to each of two directions along the surface of the skin.

- Burn sites contract much less than undamaged skin, i.e., only by $2.2 \pm 4.2\%$.

Based upon the above results, burn radii measured using excised skin should be multiplied by 1/0.978. To arrive at the correction factor for burn depth, we shall assume that skin volume remains constant. This means that burn depths should be multiplied by $(0.978)^2$.

To correct for shrinkage caused by subsequent treatment of the specimens, scaled photographs of cross sections of excised skin were compared with photographs of the same cross sections after completion of all histologic preparations. These photographs showed that the radii were reduced by $10.3 \pm 4.2\%$ while depths were reduced by $11.3 \pm 5.5\%$.

The above results indicate the following factors for correcting histologic measurements

$$(1/0.978)(1/0.897) = 1.140 \text{ for burn radii}$$

$$(0.978)^2(1/0.887) = 1.078 \text{ for burn depths.}$$

Burn Results

A total of 19 pigs were exposed to the CW CO_2 laser and 1 pig to the ruby laser. Only one pig was used for the ruby laser in that it was not sufficiently powerful to cause any burn damage.

Tables 5, 6, and 7 present the histologic determinations of the depths and radii of damage for three different CO_2 beams, namely

Power	CO_2 Beam Radius at $1/e^2$ Point
1.53 ± 0.04 watts	0.710 cm
1.97 ± 0.07 "	0.383 "
1.55 ± 0.07 "	0.383 "

The difference in power of the smaller beam (0.383 cm) was caused by a drift in power during the period between the two sets of experiments.

These tables include approximately 75% of the burn sites. Remaining burn sites were omitted because of one or more of the following reasons

- sites were too small to be evident
- sites were elliptical in shape
- specimens curled or were lost in transit.

Exposure times were controlled electronically via a shutter system with an estimated accuracy of a few hundredths of a second.

TABLE 5. HISTOLOGY RESULTS FROM CO_2 EXPOSURES
(1.53 ± 0.04 watts, beam radius at $1/e^2$ points = 0.710 cm)

Pulse duration (sec)	Number of measurements[a]	Damage radii[b] (cm)	Depths of damage[b] (cm)
03.0	23(24)	0.0997 ± 0.0432	0.0211 ± 0.0101
04.0	22(26)	0.1747 ± 0.0603	0.0357 ± 0.0170
05.0	52(52)	0.2237 ± 0.0570	0.0567 ± 0.0423
06.0	10(10)	0.2835 ± 0.0537	0.0438 ± 0.0345
10.0	22(22)	0.3708 ± 0.0582	0.1294 ± 0.0483
15.0	21(19)	0.4326 ± 0.0670	0.1419 ± 0.0410
20.0	22(20)	0.5100 ± 0.0956	0.2594 ± 0.0957
30.0	17(12)	0.5632 ± 0.0531	0.2430 ± 0.0396
40.0	19 (4)	0.6344 ± 0.0667	0.3799 ± 0.2095

[a]Radial measurements plus depth measurements given in parentheses.

[b]Dimensions corrected for tissue shrinkage.

TABLE 6. HISTOLOGY RESULTS FROM CO_2 EXPOSURES
(1.97 ± 0.07 watts, beam radius at $1/e^2$ points = 0.383 cm)

Pulse duration (sec)	Number of measurements[a]	Damage radii[b] (cm)	Depths of damage[b] (cm)
0.3	4 (4)	0.0800 ± 0.0330	0.0167 ± 0.0063
0.4	19(19)	0.1282 ± 0.0316	0.0160 ± 0.0055
0.6	28(28)	0.1940 ± 0.0333	0.0351 ± 0.0145
1.0	25(25)	0.2531 ± 0.0418	0.0290 ± 0.0127
2.0	6 (6)	0.2655 ± 0.0405	0.1004 ± 0.0246
3.0	0 (5)	–	0.1177 ± 0.0140
5.0	11(14)	0.3627 ± 0.0605	0.1878 ± 0.0446
7.5	10 (9)	0.3910 ± 0.0712	0.1476 ± 0.0527
10.0	14 (9)	0.4328 ± 0.0616	0.1749 ± 0.0566
15.0	13(11)	0.4806 ± 0.0631	0.1979 ± 0.0619

[a]Radial me[illegible]ment plus depth measurements in parentheses.

[b]Dimensions corrected for tissue shrinkage.

TABLE 7. HISTOLOGY RESULTS FROM CO_2 EXPOSURES
(1.55 ± 0.07 watts, beam radius at $1/e^2$ points = 0.383 cm)

Pulse duration (sec)	Number of measurements[a]	Damage radii[b] (cm)	Depths of damage[b] (cm)
0.3	10(10)	0.0326 ± 0.0257	0.0079 ± 0.0022
0.5	10(10)	0.1018 ± 0.0369	0.0132 ± 0.0060
2.0	10 (9)	0.2246 ± 0.0800	0.0432 ± 0.0196
5.0	14(14)	0.3082 ± 0.0218	0.1183 ± 0.0190
7.5	11(14)	0.3652 ± 0.0366	0.1784 ± 0.0197
10.0	14(14)	0.4006 ± 0.0307	0.1430 ± 0.0502
20.0	25(25)	0.4431 ± 0.0575	0.2738 ± 0.0412

[a] Radial measurements plus depth measurements given in parentheses.

[b] Dimensions corrected for tissue shrinkage.

On a percentage basis, the mean standard deviations associated with the damage radii of Tables 5, 6, and 7 are 21.3, 19.7, and 26.9%, respectively. Mean standard deviations associated with depths of damage are 47.1, 31.6, and 28.0%, respectively. In each case the radial measurements are more precise than the depth measurements due in large part to variations in skin composition and contours with depth.

Plots of the tabular results are presented in Figures 15 through 17. Again one can see the greater variability in the depth measurements.

Skin burns are evident as a consequence of discoloration. With marginal burns, the sites were a pinkish red and remained so during the 24 hours prior to sacrificing the animal. More severe burns exhibit a white area surrounded by a well-defined red ring. Radii of these circular areas were measured by means of microcalipers (finest dial reading = 0.003 cm). These measurements were made within 1 hour following exposure and immediately before sacrificing the animals. No pronounced differences were noticed in the measurements. Results are presented in Table 8.

By comparing the radii given in Table 8 with those given in Tables 5 and 6, it may be observed that the radii of the red areas correspond reasonably well with the radii of irreversible damage for each of the exposures.

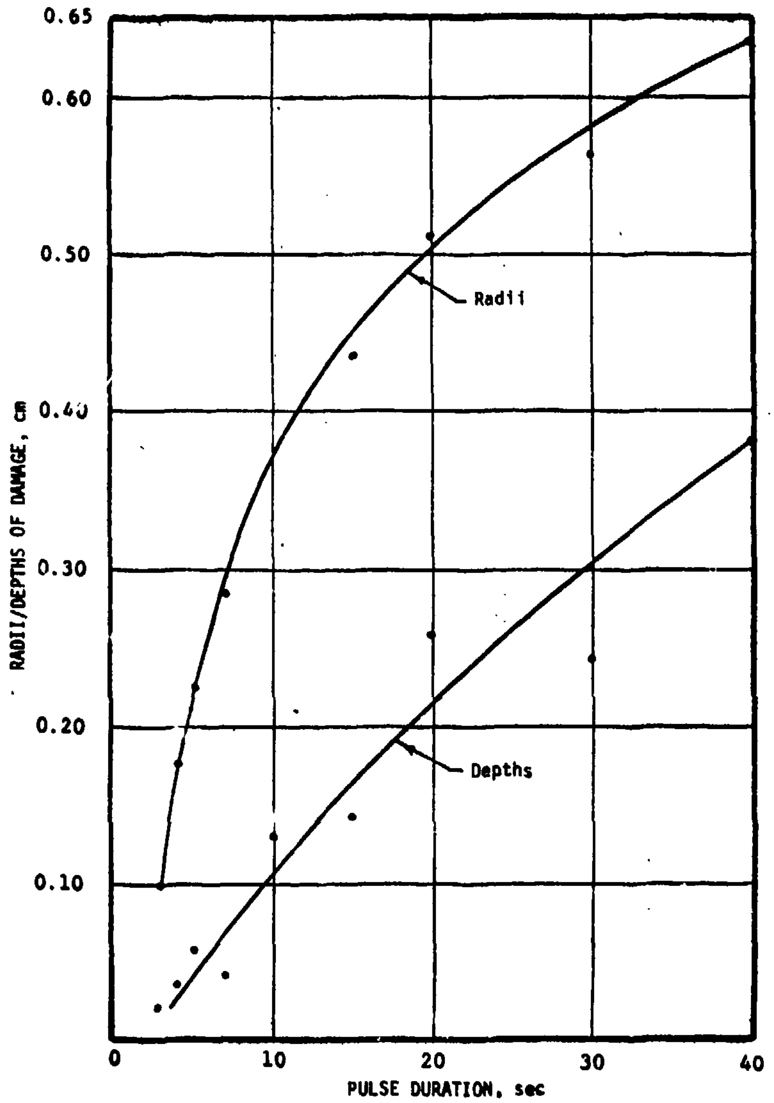


Figure 15. Radii and depths of damage produced by CO_2 laser (1.53 watts, beam radius at $1/e^2$ point = 0.710 cm).

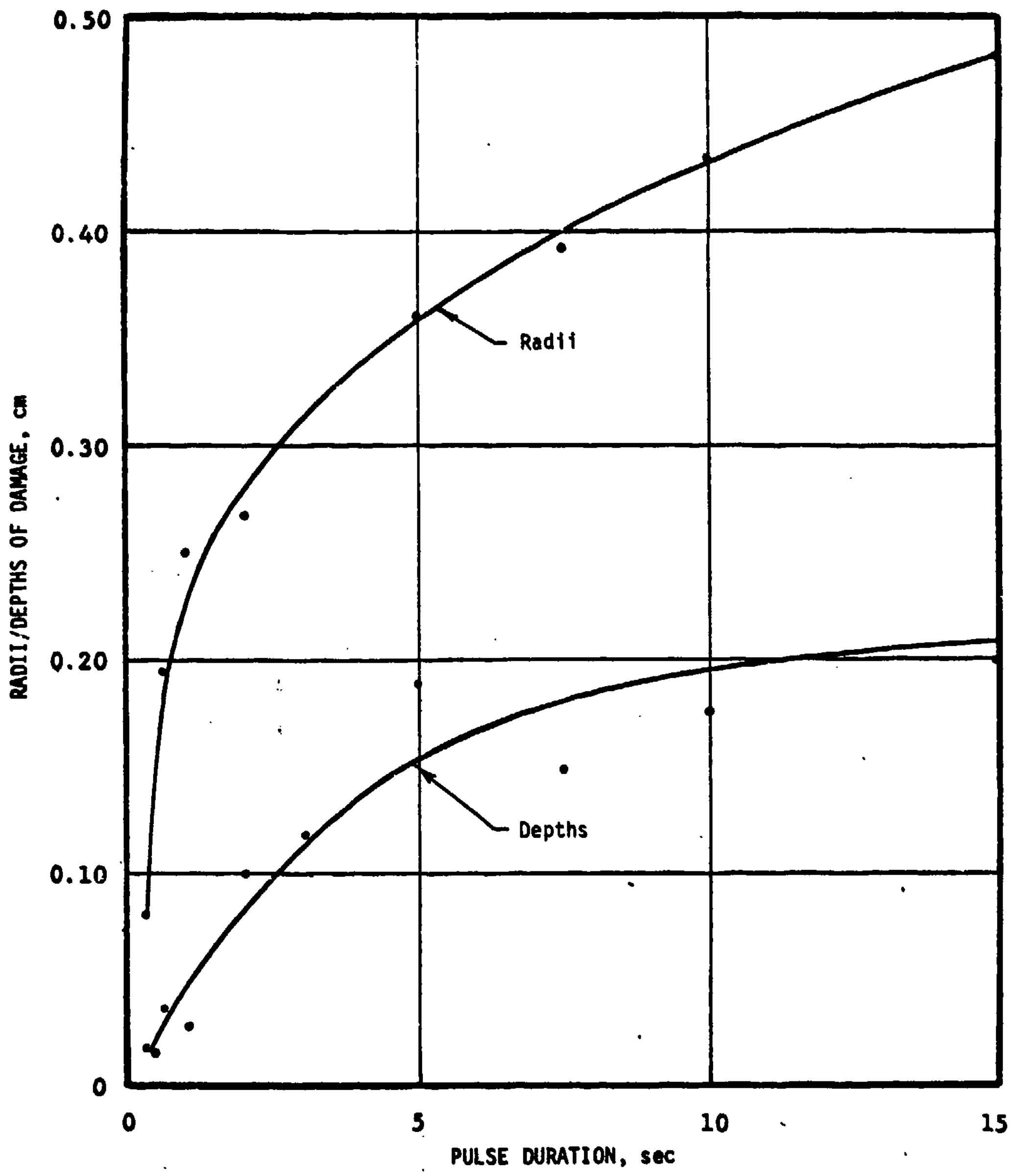


Figure 16. Radii and depths of damage produced by CO_2 laser (1.97 watts, beam radius at $1/e^2$ point = 0.383 cm).

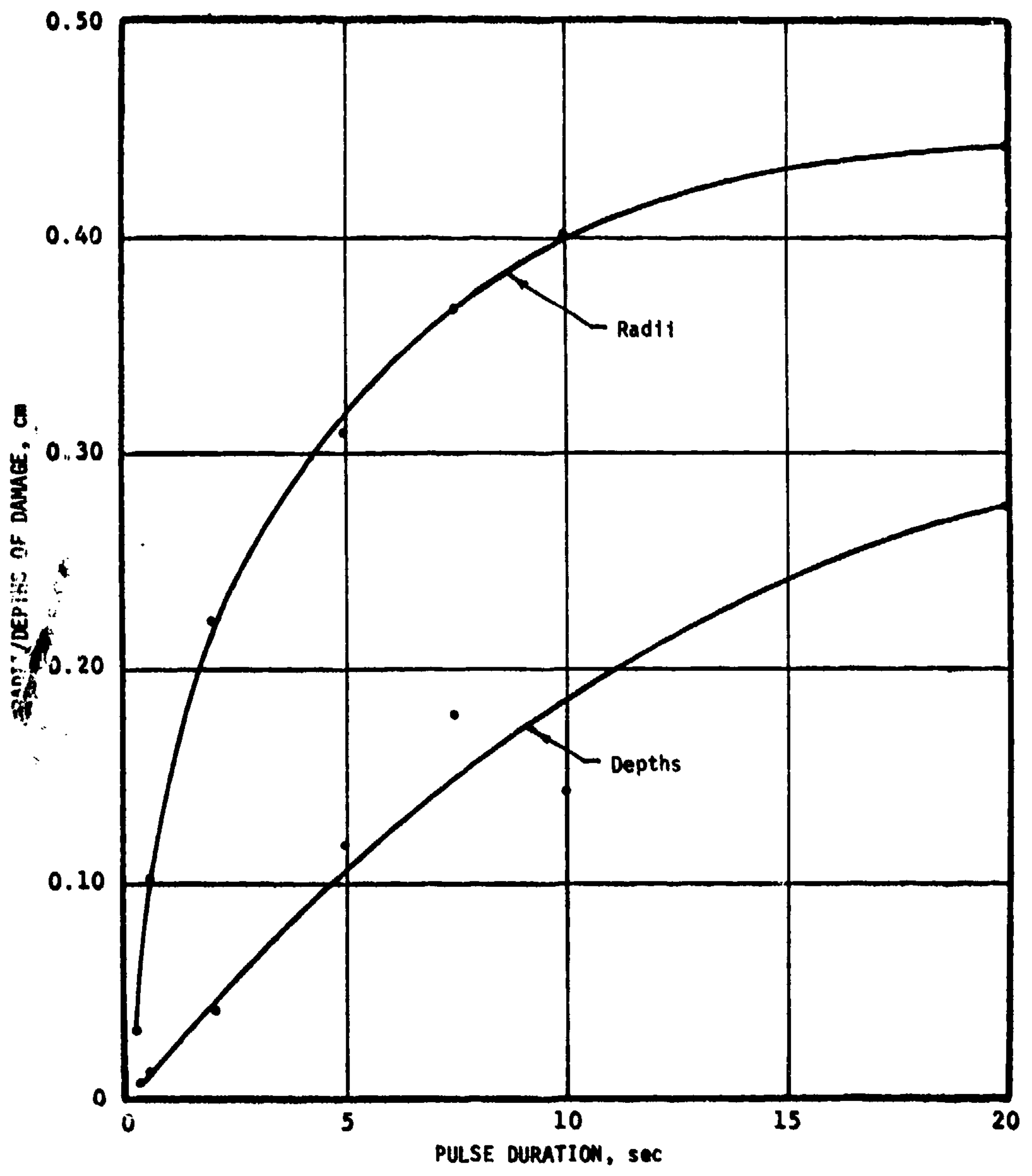


Figure 17. Radii and depths of damage produced by CO_2 laser (1.55 watts, beam radius at $1/e^2$ point = 0.383 cm).

TABLE 8. RADII OF RED, WHITE BURN AREAS PRIOR TO EXCISING SPECIMENS (CO_2 EXPOSURES)

Incident beam power (watts)	Beam radius at $1/e^2$ points (cm)	Pulse duration (sec)	Radii of red areas (cm)	Radii of white areas[a] (cm)
1.53	0.710	5.0	0.287 ± 0.011	0.177 ± 0.014
"	"	10.0	0.402 ± 0.029	0.267 ± 0.023
"	"	15.0	0.434 ± 0.036	0.316 ± 0.036
"	"	20.0	0.485 ± 0.018	0.391 ± 0.032
"	"	30.0	0.550 ± 0.031	0.444 ± 0.032
"	"	40.0	0.606 ± 0.041	0.504 ± 0.032
1.97	0.383	7.5	0.368 ± 0.027	0.342 ± 0.026
"	"	10.0	0.400 ± 0.034	0.366 ± 0.016
"	"	15.0	0.426 ± 0.024	0.392 ± 0.020

[a]"White" areas produced by 1.53-watt exposures were less distinct than those produced by 1.97-watt exposures.

Three different ruby laser exposures were used, namely

Number of exposures	Pulse energy, time	Ruby beam radius at $1/e^2$ point
12	3.48 joules (500 μsec)	0.17 cm
3	11.8 joules (500 μsec)	0.77 cm
5	5.9 joules (50 μsec)	0.77 cm

Histologic examinations of skin sites exposed to the ruby laser revealed no damage whatsoever.

Criteria for First-, Second-, and Third-Degree Burns--Third-degree burns are completely white without blisters or charring. Radii of white areas shown in Table 8 are larger than that of any blisters. The mean value of the damage integral at these radii was $(1.0 \pm 1.0)\ 10^4$. The large standard deviation is attributable to the fact that small errors in temperature (or location) produce very substantial changes in Ω.

Third-degree burns may be estimated using the above Ω value. Second-degree burns should have a Ω value of 1 based upon the agreement between the damage radii presented in Tables 5 and 6, and the red burn radii of Table 8. First-degree burns should have a Ω value of the order of 0.1 or less. More precise definition is not possible in that such burns were not evident during the course of the pig experiments.

Criterion for Fourth-Degree Burns (Steam Blisters)--Blisters form as a consequence of pressures developed internally by trapped steam. We have found that the skin separates at the epidermal/dermal interface. Measurements of the blister radius produced by 20-sec CO_2 pulses (power = 1.55 watts, beam radius = 0.383 at $1/e^2$ point) yielded values of 0.220 ± 0.073 cm. At this blister radius, the model predicted a peak temperature of 131°C. This temperature represents a simple first-order criterion for predicting the formation and growth of steam blisters. At this temperature, superheated water would develop pressures of two atmospheres.

Criterion for Fifth-Degree Burns--Fifth-degree burns arise when tissues char. Char areas are always surrounded by white and red rings. Steam blisters will usually form before the start of charring.

Charring represents a complex temperature/time dependent process (24). Tissues will char upon exposure to temperatures of a few hundred degrees centigrade and higher, depending upon the exposure times. Based upon our experiences with other organic materials we have assumed a temperature of 400°C in view of the short exposure times to such temperatures.

With the CO_2 laser power of 1.55 watts and the beam radius of 0.383 cm ($1/e^2$ points), black spots formed on blisters in 10 of 25 20-second exposures. No char was observed with 10-second exposures. To achieve epidermal temperatures of 400°C, the code indicated a heat transfer coefficient (associated with heat transfer across the vapor space) of approximately $6 \cdot 10^{-3}$ cal/cm^2-sec-°C. Heat fluxes crossing the blister space are equal to the product of the above value and the temperature difference across the blister. While these fluxes can be appreciable, they are small by comparison to conductive fluxes just prior to blister formation.

Comparison of Predicted and Experimental Radii/Depths of Irreversible Damage

CO_2 Laser Exposures--Table 9 compares predicted radii and depths of irreversible damage with their experimental counterparts. Experimental data are from Tables 5, 6, and 7. Overall it may be observed that the agreement is good. The one exception is the depths of damage produced by the long-duration exposures to 1.97 watts. This discrepancy is probably due to the presence of fat beneath the skin.

TABLE 9. COMPARISON OF PREDICTED AND EXPERIMENTAL DAMAGE RADII AND DEPTHS (CO_2 LASER)

Power, (watts)	Beam radius at $1/e^2$ point (cm)	Pulse duration (sec)	Radius of damage (cm) Exp	Radius of damage (cm) Calc	Depth of damage (cm) Exp	Depth of damage (cm) Calc
1.55	0.383	0.3	0.0326	0	0.0079	0
1.55	0.383	0.5	0.1018	0.0607	0.0132	0.0147
1.55	0.383	2.0	0.2246	0.2766	0.0432	0.0654
1.55	0.383	5.0	0.3082	0.3510	0.1183	0.1385
1.55	0.383	7.5	0.3652	0.3770	0.1784	0.2579
1.55	0.383	10.0	0.4006	0.4013	0.1430	0.2985
1.55	0.383	20.0	0.4431	0.4498	0.2738	0.3011
1.53	0.710	3.0	0.0997	0.0364	0.0211	0.0137
1.53	0.710	4.0	0.1747	0.2078	0.0357	0.0272
1.53	0.710	5.0	0.2237	0.2814	0.0567	0.0407
1.53	0.710	6.0	0.2835	0.3254	0.0438	0.0542
1.53	0.710	10.0	0.3700	0.4227	0.1294	0.1229
1.53	0.710	15.0	0.4326	0.4882	0.1419	0.1433
1.53	0.710	20.0	0.5100	0.5277	0.2594	0.2890
1.53	0.710	30.0	0.5632	0.6043	0.2430	0.2739
1.53	0.710	40.0	0.6344	0.6446	0.3799	0.3251
1.97	0.710	0.3	0.0800	0	--	--
1.97	0.710	0.4	0.1282	0.0955	0.0160	0.0169
1.97	0.710	0.6	0.1940	0.1792	0.0351	0.0277
1.97	0.710	1.0	0.2531	0.2444	0.0290	0.0456
1.97	0.710	2.0	0.2655	0.3065	0.1004	0.0695
1.97	0.710	3.0	--	0.3420	--	0.0960
1.97	0.710	5.0	0.3627	0.3754	0.1878	0.2467
1.97	0.710	7.5	0.3910	0.4081	0.1476	0.2376
1.97	0.710	10.0	0.4328	0.4290	0.1749	0.3200
1.97	0.710	15.0	0.4806	0.4531	0.1979	--

Such fat is much more difficult to damage than skin tissues, while media such as glands, and blood vessels are not. As a consequence depths of damage beneath the skin were highly dependent upon the presence of glands or blood vessels in regions of pronounced heating.

Ruby Laser Exposures--No irreversible damage was predicted for the 5.9 and 11.8 joule exposures involving a beam radius of 0.77 cm described beneath Table 8. This, of course, is what we found experimentally. However, damage was predicted as a consequence of the 3.48 joule exposure with a beam radius of 0.17 cm. The damage extended over a radius of 0.1541 cm and a depth of 0.1067 cm. This finding conflicts with the fact that no damage was found histologically. Only one explanation could be advanced for this discrepancy--namely attenuation of the laser beam by vapors/particulates released by beam impact.

Experimental results are consistent with observations of Kuhns et al. (12) and Lawrence (13). Kuhns indicates that 42 joules/cm^2 are needed to produce a slight lesion in white pig skin. If all the energy of our ruby laser were contained within 0.17 cm, the energy density would be 38.3 joules/cm^2.

To gain a better insight into the magnitude of any attenuation, a compute run was executed with the incident reduced by half. The predicted radius and depth of damage were still significant, namely, 0.1142 and 0.0558 cm, respectively. Figure 18 shows that the temperatures are very appreciable even when only half of the incident energy is considered. These results suggest that attenuation is very substantial.

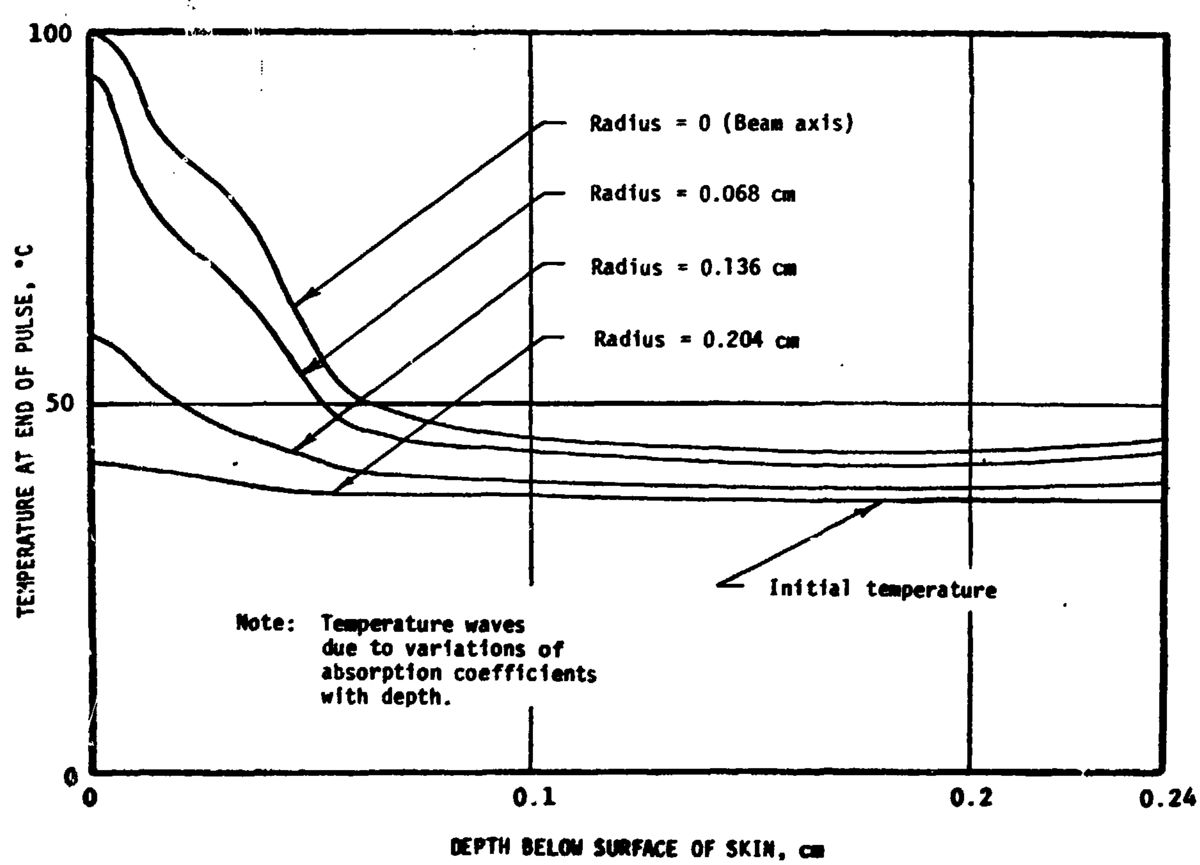


Figure 18. Temperature predictions due to ruby laser pulse (pulse energy = 1.74 joules, pulse duration = $5 \cdot 10^{-4}$ sec; beam radius = 0.17 cm at $1/e^2$ points).

SUMMARY AND CONCLUSIONS

The skin model provides a wide variety of options to the user. These include

- laser exposures involving
  - single pulses
  - multiple pulses which are identical; or have different powers, durations, and repetition rates
  - any wavelength

Beam profiles may have any shape provided they are radially symmetric. Incident beams are considered normal to the surface of the skin.

The model allows for

- differences of thermal, optical, physiological properties with depth
- temporal changes in optical/thermal properties and in water content
- blood flow variations with depth
- formation/growth of steam blisters
- heat losses to the environment
- heat losses in transforming water into steam
- interception of radiation by a hair follicle.

The model predicts transient temperatures, extent of irreversible damage, and degree of burn.

Basic techniques used to develop the model are described in the section "Skin Model" and in Appendixes A and B. Operational details are described in Appendix C. Input data for the code are given in the section "Data Needed by the Skin Model," and sample computer runs are presented in Appendix C.

Depths and radii of irreversible damage predicted by the code were generally in good agreement with those determined histologically from CO_2 laser exposures of pigs, but there was poor agreement with exposures of pigs to our ruby laser. In this case, the model predicted appreciable damage while none was evident from histologic observations. We suspect that the discrepancy is due to the attenuation of the beam by vapors and particulates rather than due to data errors. Material discharge was observed on impacting the skin by the intense ruby pulses. Similar discharge was not produced by the CO_2 beam in that the CO_2 laser power is several orders of magnitude less than the ruby laser.

Beam attenuation, if such is the cause of the above discrepancy, is very appreciable. Model runs indicate that beam intensities must be reduced by more than half before damage becomes insignificant. This aspect of the problem remains to be resolved. For this reason, we recommend that analytical/experimental studies be undertaken to determine the conditions under which attenuation becomes important and devise means to account for such in the model. Unless this is done, large uncertainties will exist in the model predictions involving rapid delivery of energy.

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APPENDIX A

FINITE-DIFFERENCE METHOD USED TO CALCULATE TEMPERATURES

INTRODUCTION

In this appendix we shall describe the finite-difference technique for predicting transient temperatures in biological tissues. The technique provides for a wide variety of thermal conditions and was originally developed by Peaceman and Rachford (17). Subsequently it was applied to problems involving cylindrical coordinates by Mainster (14) and then by Takata (23) to predict laser-induced thermal damage to eyes.

In essence the method is based upon finite-differences in which thermal gradients associated with one of the coordinates are treated implicitly while the gradients in the other coordinate are treated explicitly. This procedure is reversed following each set of calculations. The result is stable, accurate temperature predictions using time step orders of magnitude larger than those required by standard explicit finite-difference techniques.

Here we have upgraded the technique to accommodate

- heat losses to the environment
- thermal effects of variable blood flow with depth
- steam blisters
- heat losses due to the generation of escaping steam
- temporal as well as spacial variations of thermal properties

FINITE-DIFFERENCE TECHNIQUE

Three assumptions are made in developing the finite-difference equations. These are

- Initially the biological media is at a uniform temperature. Biological heating is neglected.
- Blood flow acts as a heat sink in which blood enters incremental small tissue volumes at the initial body temperature of the tissues and

leaves at the tissue temperature. Changes in the blood flow with temperature are neglected.

- The heat-transfer coefficient associated with environmental heat exchange is considered constant independent of temperature.

These assumptions do not reflect upon the capabilities of the method and can easily be upgraded or eliminated according to how well one is able to quantify each of the phenomena for specific individuals and environmental conditions.

Spacial Grid

To conserve on computational time, an expanding grid is used as illustrated in Figure A-1. Within regions of greatest heat deposition, small uniform Δr, Δz spacial increments are selected. Here the region of most pronounced heating is considered located just below the surface as would be the case for skin burns. In this figure, the first N1 radial increments, i.e. Δr_1, Δr_2 ... Δr_{N1} are equal as are the first M1 axial increments Δz_1, Δz_2 ... Δz_{M1}. Beyond the uniform grid, the radial and axial increments are progressively increased as follows:

$$\Delta r_{j+1} = C_1 \Delta r_j, \quad j = N1 \text{ to } N \tag{A-1}$$

$$\Delta z_{i+1} = C_2 \Delta z_i, \quad i = M1 \text{ to } M \tag{A-2}$$

One important condition needs to be satisfied in selecting the grid--that is that the expanded grid must extend into regions of negligible temperature rise.

Problem Definition

In the equations to follow, all tissue temperatures v are measured from the environmental temperature v_e to simplify calculations of environmental heat transfer.

<u>Heat Conduction Equation</u>:

$$\rho C \frac{\partial v}{\partial t} = \bar{q} + \frac{K}{r}\frac{\partial v}{\partial r} + \frac{\partial}{\partial r}\left(K\frac{\partial v}{\partial r}\right) + \frac{\partial}{\partial z}\left(K\frac{\partial v}{\partial z}\right) - \bar{B}C_b v - \bar{\bar{q}} \tag{A-3}$$

<u>Initial Condition</u>:

$$v = v_o - v_e \tag{A-4}$$

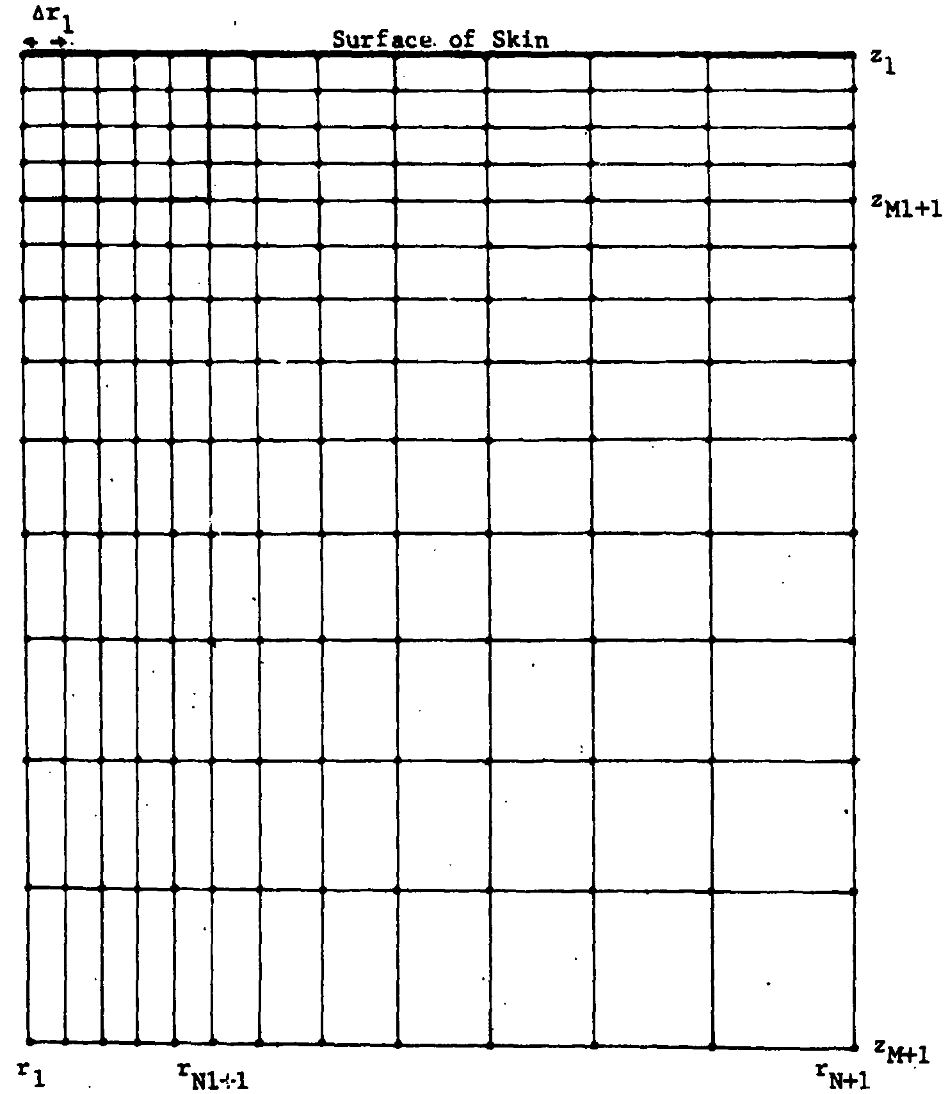

Figure A-1. Radial and axial grid points and increments.

<u>Boundary Conditions</u>:

$$K\frac{\partial v}{\partial r} = 0 \qquad \text{at } r = 0, \text{ all } t \qquad \text{(A-5)}$$

$$-K\frac{\partial v}{\partial z} = -h_e v \qquad \text{at } z = 0, \ t > 0 \qquad \text{(A-6)}$$

$$v \rightarrow v_o - v_e \qquad \text{as } r \rightarrow \infty, \ z \rightarrow \infty \qquad \text{(A-7)}$$

<u>Steam Blisters</u>:

$$-K\frac{\partial v}{\partial z}\Big|_{z_w-\delta} = -K\frac{\partial v}{\partial z}\Big|_{z_w+\delta} = h_w\left(v\Big|_{z_w-\delta} - v\Big|_{z_w+\delta}\right) \qquad \text{(A-8)}$$

Finite-Difference Approximations

The following finite-difference approximations are used to represent the various partial derivatives of equation A-3, subject to the gradients at various boundaries expressed by equations A-5, A-6, and A-8 for time index k.

$$\frac{K}{r}\left(\frac{\partial v}{\partial r}\right)\Big|_{i,j} \simeq \frac{K_{i,j}}{r_j}\left[\frac{v_{i,j+1,k} - v_{i,j-1,k}}{r_{j+1} - r_{j-1}}\right], \ j = 2, \ \ldots \ N, \text{ all } i$$

$$= 0, \ j = 1, \text{ all } i \qquad \text{(A-9)}$$

$$\frac{\partial}{\partial r}\left(K\frac{\partial v}{\partial r}\right)\Big|_{i,j}$$

$$\simeq \frac{2K_{i,j}}{r_{j+1}-r_{j-1}}\left[\frac{v_{i,j+1,k} - v_{i,j,k}}{r_{j+1} - r_j} - \frac{v_{i,j,k} - v_{i,j-1,k}}{r_j - r_{j-1}}\right]$$

$$+ \frac{K_{i,j+1} - K_{i,j-1}}{r_{j+1} - r_{j-1}}\left[\frac{v_{i,j+1,k} - v_{i,j-1,k}}{r_{j+1} - r_{j-1}}\right], \ j = 2, \ \ldots \ N, \text{ all } i$$

$$\simeq \frac{2K_{i,1}}{\Delta r_1^2}(v_{i,2,k} - v_{i,1,k}), \ j = 1, \text{ all } i \qquad \text{(A-10)}$$

$$\frac{\partial}{\partial z}\left(K\frac{\partial v}{\partial z}\right)\Big|_{i,j}$$

$$\simeq \frac{2K_{i,j}}{z_{i+1} - z_{i-1}}\left[\frac{v_{i+1,j,k} - v_{i,j,k}}{z_{i+1} - z_i} - \frac{v_{i,j,k} - v_{i-1,j,k}}{z_i - z_{i-1}}\right]$$

$$+ \frac{K_{i+1,j} - K_{i-1,j}}{z_{i+1} - z_{i-1}}\left[\frac{v_{i+1,j,k} - v_{i-1,j,k}}{z_{i+1} - z_{i-1}}\right], \quad i = 2, \ldots M, \text{ all } j$$

$$\simeq \frac{K_{1,j,k} + K_{2,j,k}}{\Delta z_1{}^2}(v_{2,j,k} - v_{1,j,k}) - \frac{h_e}{\Delta z_1}(v_{1,j,k} + v_{1,j,k+1/2}),$$

$$i = 1, \text{ all } j \qquad \text{(A-11)}$$

Steam blisters are allowed to form or spread radially whenever a given temperature is achieved at the depth z_I. For values of I greater than 2, the following two equations replace the particular expressions of equation A-11 with i, j values associated with the blister.

$$\frac{\partial}{\partial z}\left(K\frac{\partial v}{\partial z}\right)\Big|_{I-1,j} = \frac{2}{z_I - z_{I-2}}\Bigg[h_w(v_{I,j,k} - v_{I-1,j,k})$$

$$- K_{I-1,j}\left[\frac{v_{I-1,j,k} - v_{I-2,j,k}}{z_{I-1} - z_{I-2}}\right]\Bigg] \qquad \text{(A-12)}$$

$$\frac{\partial}{\partial z}\left(K\frac{\partial v}{\partial z}\right)\Big|_{I,j} = \frac{2}{z_{I+1} - z_{I-1}}\Bigg[K_{I,j}\left[\frac{v_{I+1,j,k} - v_{I,j,k}}{z_{I+1,j} - z_{I,j}}\right]$$

$$- h_w(v_{I,j,k} - v_{I-1,j,k})\Bigg] \qquad \text{(A-13)}$$

For half time steps, one merely replaces k by k+1/2. For an I value of 2 one uses the following expressions.

$$\frac{\partial}{\partial z}\left(K\frac{\partial v}{\partial z}\right)\Big|_{1,j}$$

$$= \frac{1}{\Delta z_1}\left[- h_e(v_{1,j,k} + v_{1,j,k+1/2}) - 2h_w(v_{1,j,k} - v_{2,j,k})\right] \qquad \text{(A-14)}$$

$$\frac{\partial}{\partial z}\left(K\frac{\partial v}{\partial z}\right)\Big|_{2,j} = \frac{2}{z_3}\left[h_w\cdot(v_{1,j,k} - v_{2,j,k}) + \frac{(K_{2,j} + K_{3,j})}{2(z_3 - z_2)}\right.$$

$$\left.\cdot(v_{3,j,k} - v_{2,j,k})\right] \qquad \text{(A-15)}$$

Finally the expression for rates of temperature change is simply described as follows:

$$\rho C\frac{\partial v}{\partial t}\Big|_{i,j,k+1/2} = \frac{2\rho_{i,j}C_{i,j}}{\Delta t_k}(v_{i,j,k+1/2} - v_{i,j,k}),\ \text{all } i,\ j,\ k \qquad \text{(A-16)}$$

where $$\Delta t_k = t_{k+1} - t_k \qquad \text{(A-17)}$$

Finite-Difference Equations

Here half-time steps $\Delta t_k/2$ are considered. During the first half-time step, radial gradients are treated explicitly while axial gradients are treated implicitly. This set of equations is termed ROW. During the second half-time step, the radial gradients are treated implicitly while the axial gradients are treated explicitly. This set of equations is termed COLUMN.

Substituting the finite-difference approximations of equations A-9, A-10, A-11 and A-16 into equation A-3 yields the following set of equations:

ROW:

$$- A_1(i,j)v_{i-1,j,k+1/2} + (A_2(i,j) + 2\rho_{i,j}C_{i,j}/\Delta t_k)v_{i,j,k+1/2}$$

$$- A_3(i,j)v_{i+1,j,k+1/2} = B_1(i,j)v_{i,j-1,k} - B_2(i,j)v_{i,j,k}$$

$$+ B_3(i,j)v_{i,j+1,k} + 2\rho_{i,j}C_{i,j}v_{i,j,k}/\Delta t_k + \bar{q}_{i,j,k+1/2}$$

$$- \bar{\bar{q}}_{i,j,k+1/2} \qquad \text{(A-18)}$$

COLUMN:

$$- B_1(i,j)v_{i,j-1,k+1} + (B_2(i,j) + 2\rho_{i,j}C_{i,j}/\Delta t_k)v_{i,j,k+1}$$

$$- B_3(i,j)v_{i,j+1,k+1} = A_1(i,j)v_{i-1,j,k+1/2} - A_2(i,j)v_{i,j,k+1/2}$$

$$+ A_3(i,j)v_{i+1,j,k+1/2} + 2\rho_{i,j}C_{i,j}\ v_{i,j,k+1/2}/\Delta t_k + \bar{q}_{i,j,k+1/2} - \bar{\bar{q}}_{i,j,k+1/2} \qquad \text{(A-19)}$$

Expressions for the coefficients A_1, A_2, A_3, B_1, B_2, and B_3 are presented below

$$\left.\begin{aligned} A_1(i,j) &= K_{i,j}Z_1(i) + (K_{i+1,j} - K_{i-1,j})Z_2(i) \\ A_2(i,j) &= K_{i,j}Z_3(i) + \bar{B}_iC_b/2 \\ A_3(i,j) &= K_{i,j}Z_4(i) - (K_{i+1,j} - K_{i-1,j})Z_2(i) \end{aligned}\right\} i = 2, \ldots M, \text{ all } j \qquad \text{(A-20)}$$

$$A_1(i,j) = 0$$

$$A_2(i,j) = \frac{K_{1,j} + K_{2,j}}{(\Delta z_1)^2} + \frac{h_e}{\Delta z_1} + \bar{B}_1C_b/2 \quad i = 1, \text{ all } j$$

$$A_3(i,j) = \frac{K_{1,j} + K_{2,j}}{(\Delta z_1)^2} \qquad \text{(A-21)}$$

$$\left.\begin{aligned} B_1(i,j) &= K_{i,j}R_1(j) + (K_{i,j+1} - K_{i,j-1})R_2(j) \\ B_2(i,j) &= K_{i,j}R_3(j) + \bar{B}_iC_b/2 \\ B_3(i,j) &= K_{i,j}R_4(j) - (K_{i,j+1} - K_{i,j-1})R_2(j) \end{aligned}\right\} j = 2, \ldots N, \text{ all } i \qquad \text{(A-22)}$$

$$\left.\begin{aligned} B_1(i,1) &= 0 \\ B_2(i,1) &= \frac{K_{i,2} + K_{i,1}}{(\Delta r_1)^2} + \bar{B}_iC_b/2 + \frac{h_e}{\Delta z_1} \\ B_3(i,1) &= \frac{K_{i,2} + K_{i,1}}{(\Delta r_1)^2} \end{aligned}\right\} j = 1, \text{ all } i \qquad \text{(A-23)}$$

Whenever a steam blister forms or grows, one should replace those A_1, A_2, and A_3 coefficients having i values of I and I-1. When I > 2 the coefficients are:

$$A_1(I-1,j) = K_{I-1,j}Z_1(I-1)$$

$$A_2(I-1,j) = K_{I-1,j}Z_1(I-1)+\bar{B}_{I-1}C_b/2 + h_wZ_5(I-1)$$

$$A_3(I-1,j) = h_wZ_5(I-1)$$

$$A_1(I,j) = 2h_wZ_5(I)$$

$$A_2(I,j) = K_{I,j}Z_4(I) + \bar{B}_IC_b/2 + h_wZ_5(I)$$

$$A_3(I,j) = K_{I,j}Z_4(I) \tag{A-24}$$

If I = 2 one should replace those A_1, A_2, and A_3 coefficients having i values of 1 and 2 by

$$A_2(1,j) = (h_e + 2h_w)/z_1 + \bar{B}_1C_b/2$$

$$A_3(1,j) = 2h_w/z_1$$

$$A_1(2,j) = 2h_w/z_3$$

$$A_2(2,j) = 2h_w/z_3 + (K_{2,j} + K_{3,j})/(z_3(z_3-z_2)) + \bar{B}_2C_b/2$$

$$A_3(2,j) = (K_{2,j} + K_{3,j})/(z_3(z_3-z_2)) \tag{A-25}$$

In equations A-20 through A-25 the functions, R_1, ... R_4, Z_1, ... Z_5 depend only upon the grid variables r_j, z_i as described below

$$Z_1(i) = \frac{2}{(z_{i+1} - z_{i-1})(z_i - z_{i-1})} \tag{A-26}$$

$$Z_2(i) = -\frac{1}{(z_{i+1} - z_{i-1})^2} \tag{A-27}$$

$$Z_3(i) = -\frac{2}{(z_{i+1} - z_{i-1})(z_{i+1} - z_i)} + \frac{2}{(z_{i+1} - z_{i-1})(z_i - z_{i-1})} \tag{A-28}$$

$$Z_4(i) = \frac{2}{(z_{i+1} - z_{i-1})(z_{i+1} - z_i)} \tag{A-29}$$

$$Z_5(i) = \frac{2}{z_{i+1} - z_{i-1}} \tag{A-30}$$

$$R_1(j) = -\frac{1}{r_j(r_{j+1} - r_{j-1})} + \frac{2}{(r_{j+1} - r_{j-1})(r_j - r_{j-1})} \tag{A-31}$$

$$R_2(j) = -\frac{1}{(r_{j+1} - r_{j-1})^2} \tag{A-32}$$

$$R_3(j) = \frac{2}{(r_{j+1} - r_{j-1})(r_{j+1} - r_j)} + \frac{2}{(r_{j+1} - r_{j-1})(r_j - r_{j-1})} \tag{A-33}$$

$$R_4(j) = \frac{1}{r_j(r_{j+1} - r_{J-1})} + \frac{2}{(r_{J+1} - r_{j-1})(r_{j+1} - r_j)} \tag{A-34}$$

In matrix form, equation A-18 and equation A-19 are of tridiagonal form with non-zero elements along the main diagonal and on either side of the diagonal. Means for solving such matrices are described by Takata et al. (23) and involve simple algebraic solution of each set of equations for ROW and COLUMN. To illustrate the procedure consider the first two expressions of equation A-18 wherein i = 1 and 2. These expressions are given below.

$$(A_2(1,j) + 2\rho_{1,j}C_{1,j}/\Delta t_k)v_{1,j,k+1/2} - A_3(1,j)v_{2,j,k+1/2}$$

$$= G_{1,j} \tag{A-35}$$

$$-A_1(2,j)v_{1,j,k+1/2} + (A_2(2,j) + 2\rho_{2,j}C_{2,j}/\Delta t_k)v_{2,j,k+1/2}$$

$$-A_3(2,j)v_{3,j,k+1/2} = G_{2,j} \tag{A-36}$$

where $G_{1,j}$ and $G_{2,j}$ represent the values of the right-hand side of equation A-18.

First equation A-35 is solved for $v_{1,j,k+1/2}$ and used to eliminate $v_{1,j,k+1/2}$ from equation A-36. The resultant equation is then solved for $v_{2,j,k+1/2}$ and used to eliminate $v_{2,j,k+1/2}$ from the next expression (i = 3) of equation A-18. By repeating the process for all M+1 expressions of equation A-18, one arrives at the following set of equations.

$$
\left.\begin{aligned}
&v_{i,j,k+1/2} - \frac{A_3(1,j)}{F_1} v_{2,j,k+1/2} = D_1 \\
&v_{2,j,k+1/2} - \frac{A_3(2,j)}{F_2} v_{3,j,k+1/2} = D_2 \\
&\quad\vdots \\
&v_{M-1,j,k+1/2} - A_3(M-1,j) v_{M,j,k+1/2} = D_{M-1} \\
&v_{M,j,k+1/2} = D_M
\end{aligned}\right\} \quad \text{(A-37)}
$$

$$
\left.\begin{aligned}
&\text{for } i \text{ equal to } 1: \\
&F_1 = A_2(1,j) + 2\rho_{1,j}C_{1,j}/\Delta t_k \\
&E_1 = -A_3(1,j)/F_1 \\
&D_1 = G_{1,j}/F_1 \\
&\text{for } i \text{ greater than } 1: \\
&F_i = A_2(i,j) + 2\rho_{i,j}C_{i,j}/\Delta t_k + A_1(i,j)E_{i-1} \\
&E_i = -A_3(i,j)/F_i \\
&D_i = (G_{i,j} + A_1(i,j)D_{i-1})/F_i
\end{aligned}\right\} \quad \text{(A-38)}
$$

To solve equation A-37 for a specific value of j, one first evaluates each of the terms D_i, E_i, and F_i of equation A-38 for i values ranging from 1 to M. Then the temperatures $v_{i,j,k+1/2}$ are computed starting with i=M and ending with i=1 for particular values of j. The result is described below:

$$
\begin{aligned}
&v_{M,j,k+1/2} = D_M \\
&v_{M-1,j,k+1/2} = D_{M-1} + \frac{E_{M-1}}{F_{M-1}} v_{M,j,k+1/2} \qquad \text{(A-39)} \\
&\quad\vdots \\
&v_{1,j,k+1/2} = D_1 + \frac{E_1}{F_1} v_{2,j,k+1/2}
\end{aligned}
$$

The procedure for solving equation A-19 is the same as that described above for ROW. In doing so the arrays A_1, A_2, and A_3 of equations A-37 and A-38 are replaced by B_1, B_2, and B_3; the $G_{i,j}$ array assumes the values of the right-hand side of equation A-19; and i is held fixed while j is allowed to vary from 1 to N. Order of the ROW and COLUMN calculations is not important.

In solving equations A-18 and A-19, all terms on the right-hand side of these equations are known apriori except for the array $\bar{\bar{q}}_{i,j,k+1/2}$. This array describes the rate of heat losses in transforming water into escaping steam and is zero unless steam is being generated. At the start of each full-time step Δt_k, all elements of the array $\bar{\bar{q}}_{i,j,k+1/2}$ are set equal to zero. Then the ROW and COLUMN calculations are performed. If none of the predicted temperatures exceeds the temperature X_w of boiling water, the computations are completed. Otherwise estimates are introduced for $\bar{\bar{q}}$ at the locations of excessive temperature. Following each set of temperature calculations the trial $\bar{\bar{q}}$ values are revised according to temperature deviations from that of boiling water, and a new set of temperature calculations is conducted. Each set of calculations utilizes temperatures computed from the previous time step. Usually 4 trials are needed to arrive at the appropriate $\bar{\bar{q}}$ values.

Once water is expended from as element, the particular $\bar{\bar{q}}_{i,j,k+1/2}$ values are set equal to zero. This, of course, allows temperatures to rise above the temperature of boiling water.

Two techniques are used to determine $\bar{\bar{q}}_{i,j,k+1/2}$. Each technique computes additive changes to the previous $\bar{\bar{q}}_{i,j,k+1/2}$ values. The first technique provides fine refinements and is presented below.

$$\Delta\bar{\bar{q}} = Z_w(v_{i,j,k+1} - X_w)\rho_{i,j}C_{i,j}/\Delta t_k \tag{A-40}$$

The magnitude of the above correction is controlled via the dimensionless factor Z_w. Unless one encounters a problem of convergence, this factor is set equal to 1. When $Z_w = 1$, the numerator of equation A-40 represents the excess sensible heat per unit volume.

The second technique yields larger $\bar{\bar{q}}$ corrections, and is used when much of the heat absorbed from the laser escapes to other grid elements. In such instances, larger corrections are needed to achieve $\bar{\bar{q}}$ values of the proper magnitude with the fewest trials. Choice between the two techniques is made by comparing the absorbed heat with the rise in sensible heat when all $\bar{q}_{i,j,k+1/2}$ values are zero. $\bar{q}$ corrections are estimated by the second technique as follows:

$$\Delta\bar{q} = \frac{Z_w(X_w - v_{i,j,k+1})}{(v_{i,j,k+1} - vs_{i,j,k+1})} \cdot \bar{\bar{q}}_{i,j,k+1/2} \qquad \text{(A-41)}$$

where $vs_{i,j,k+1}$ and $v_{i,j,k+1}$ represent the temperatures before and following the $\bar{q}_{i,j,k+1/2}$ change. The denominator represents the temperature change produced by the previous $\Delta\bar{q}$; while $X_w - v_{i,j,k+1}$ represents the desired temperature change needed to yield the temperature of boiling water at 1 atmosphere of pressure.

The expressions given by equations A-40 and A-41 are only used if the resultant $\bar{q}$ values do not abstract more heat than allowed by the available water. If the available water is too small, then $\bar{q}$ is set equal to the following expression

$$\bar{q}_{i,j,k+1/2} = w_{i,j}\ Q/\Delta t_k \qquad \text{(A-42)}$$

The numerator represents the amount of heat necessary to transform the remaining water into steam. Once the water is expended, temperatures will rise above that for boiling.

Generally 4 sets of temperature calculations are required to closely approximate the $\bar{q}_{i,j,k+1/2}$ values needed to achieve temperatures of boiling water.

Immediately thereafter, the mass of escaping steam is subtracted from the amount of water per cm^3 surrounding each of the affected grid points. Once the water has been expended from the media surrounding a particular grid point, all future $\bar{q}$ are zero for the grid point. This, of course, allows temperatures to rise without bounds.

Errors

Errors associated with the method are discussed by Mainster (14). In his paper Mainster indicated that he could maintain excellent computational accuracies in spite of sequential increases of the time steps. This was true with $K\Delta t/(\rho C\Delta z^2)$ or $K\Delta t/(\rho C\Delta r^2)$ values as large as $3\cdot 10^4$. We concur with this finding provided the temporal/spacial derivatives of the thermal gradients are not excessively large. It is not true immediately following abrupt pronounced changes of heating such as at the start or end of a laser pulse. At such times it is necessary to use small time steps approximating those required by standard explicit finite-difference. Subsequent time steps may be increased. In this regard we have found that the time steps may be expanded sequentially by a constant factor without adversely degrading accuracy as follows

$$\Delta t_{k+1} = C_3 \Delta t_k \tag{A-43}$$

To maintain accuracies of the order of a few percent or less, C_3 should not exceed approximately 1.4. Accuracy will be improved, of course, with smaller C_3 values.

<u>Nomenclature</u>

A_1, A_2, A_3	coefficients of temperatures
$\bar{B}$	blood flow per unit volume of tissue, g/cm^3-sec
B_1, B_2, B_3	coefficients of temperatures
C	specific heat, cal/g-°C
C_1, C_2, C_3	factors used to expand radial increments, axial increments and time steps, respectively, dimensionless
h	heat-transfer coefficient, cal/cm^2-sec-°C
i	index associated with axial grid increments or nodal points
I	i index associated with all axial grid points at depth of blister formation
j	index associated with radial grid increments or nodal points
k	index of time steps
K	thermal conductivity, cal/cm-sec-°C
M	total number of axial increments
M1	number of uniform axial increments
N	total number of radial increments
N1	number of uniform radial increments

Q	heat of evaporation for water, cal/g
$q(r,z)$	radiant intensity per unit area, cal/cm^2-sec
$\bar{q}$	rate of heat deposition into unit volume of tissue, cal/cm^3-sec
$\bar{\bar{q}}$	rate of heat loss per unit volume of tissue due to the generation and escape of steam, cal/cm^3-sec
r	radius, cm
t	elapsed time from start laser exposure, sec
v	temperature, °C
w	mass of water per unit volume of tissue, g/cm^3
X_w	temperature of boiling water (1 atm. of pressure), °C
z	depth, cm
Z_w	dimensionless factor used for purposes of convergence, usually equals 1
z_w	depth of steam blister, cm
δ	incrementally small distance approaching zero, cm
ρ	density, g/cm^3

<u>Subscripts</u>

b	blood
e	environment
i, j	see above
k	see above
M, M1	see above
N, N1	see above

o	initial or incident value
w	steam blister

APPENDIX B

APPROXIMATE TECHNIQUE FOR REDUCING COMPUTATIONAL TIMES OF LONG PULSE TRAINS (NON-CODED PULSES - CONSTANT LASER POWERS/TIMES)

INTRODUCTION

Long pulse trains involve numerous flux or power changes. These numerous changes require many time steps because time steps can only be expanded geometrically during periods of constant flux such as during and between pulses. Immediately following the start or end of each pulse, it is necessary to return to small time steps to preserve accuracy.

Two options may be used to minimize the number of time steps. The first applies to situations in which temporal changes in the thermal properties are of negligible importance, and all boundary conditions are independent or linearly dependent upon temperature. Under such conditions, the temperature rises produced by each pulse are independent of each other. This allows one to calculate the temperature rises produced by a single pulse, and simply sum the contributions from each pulse allowing for time differences. This technique was used for the eye models (23).

Figure B-1 illustrates the technique for treating multiple pulses allowing for temporal changes in the thermal or optical properties. In essence the method eliminates many flux changes by replacing several consecutive pulses by a single "pulse" having the mean flux needed to conserve energy from the several pulses. In doing so, selected pulses are preserved to afford accurate temperature/damage predictions during representative pulses of the train. Incremental damage predicted during the selected pulses is then weighted to account for all pulses.

ACCURACY

This section assesses the consequence of using mean flux upon temperatures produced during succeeding pulses. The total number of pulses shall be designated by n_1+n_2, with the first n_1 pulses replaced by the mean flux. The remaining n_2 pulses shall be preserved and shown at the center of the first group of pulses shown in Figure B-1. Accuracy will be determined by comparing temperatures predicted during the last of the n_1+n_2 pulses with exact temperatures in which all pulses

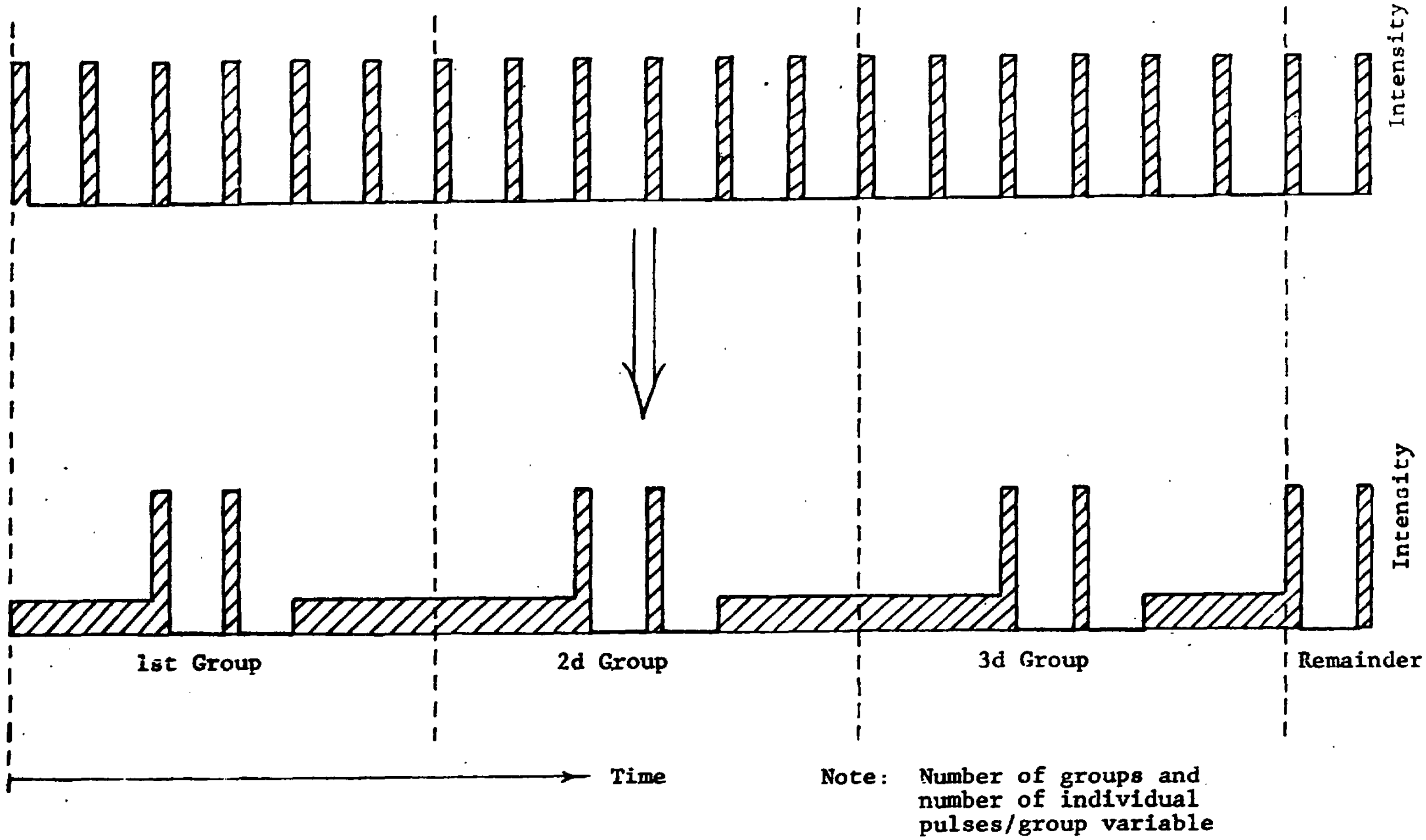

Figure B-1. Scheme for grouping large numbers of laser pulses.

are preserved. For this purpose we shall consider a semi-infinite body in which the flux is uniformly distributed over the surface. The energy will be considered entirely absorbed by the surface.

To arrive at the exact surface temperature rises we shall apply Duhamel's Principle to the solution (3) for the surface temperature rises produced by a constant flux. The temperature rise T_s at the beginning of the last of the n_1+n_2 pulses is given by

$$T_s = \frac{2q}{\sqrt{\pi K \rho C}} \sum_{n=1}^{n_1+n_2-1} \left(\sqrt{n\tau_o} - \sqrt{n\tau_o - \tau} \right) \qquad \text{(B-1)}$$

while the temperature rise at the end of the last pulse is given by

$$T_e = \frac{2q}{\sqrt{\pi K \rho C}} \sum_{n=0}^{n_1+n_2-1} \left(\sqrt{n\tau_o + \tau} - \sqrt{n\tau_o} \right) \qquad \text{(B-2)}$$

where

q = flux during each pulse, cal/cm^2-sec

K = thermal conductivity, cal/cm-sec-°C

ρ = density, g/cm^3

C = specific heat, cal/g-°C

τ_o = reciprocal of repetition rate, sec

τ = pulse width, sec

Using the mean laser flux of $\tau q/\tau_o$, yields the approximate values $\overline{T}_s$ and $\overline{T}_e$ for T_s and T_e, respectively, presented below:

$$\overline{T}_s = \frac{2\tau q}{\tau_o \sqrt{\pi K \rho C}} \left(\sqrt{(n_1+n_2-1)\tau_o} - \sqrt{(n_2-1)\tau_o} \right)$$

$$+ \frac{2q}{\sqrt{\pi K \rho C}} \sum_{n=1}^{n_2-1} \left(\sqrt{n\tau_o} - \sqrt{n\tau_o - \tau} \right) \qquad \text{(B-3)}$$

$$\bar{T}_e = \frac{2\tau q}{\tau_o\sqrt{\pi K\rho C}} \left(\sqrt{(n_1+n_2-1)\tau_o+\tau} - \sqrt{(n_2-1)\tau_o+\tau} \right)$$

$$+ \frac{2q}{\sqrt{\pi K\rho C}} \sum_{n=0}^{n_2-1} \left(\sqrt{n_o + \tau} - \sqrt{n\tau_o} \right) \qquad \text{(B-4)}$$

In examining equations B-1 through B-4 it may be noticed that the ratios $T_s/\bar{T}_s$ and $T_e/\bar{T}_e$ are independent of the flux q and thermal properties K, ρ and C. They do however depend upon τ/τ_o and upon the values for n_1 and n_2. Results of evaluating these ratios on a computer are presented in Tables B-1 through B-3 as a function of n_1 and n_2 for three τ/τ_o values. It may be observed that the agreement improves with the number of pulses n_1 and n_2 for each of the three τ/τ_o values used, namely 0.1, 0.001 and 0.00001. The best agreement is achieved with the smallest τ/τ_o value, namely 0.00001. This value is more typical of the values associated with pulsed lasers than the other two values employed.

Of primary concern is the minimum number of individual pulses n_2 to achieve accurate temperatures. In examining Tables B-1 through B-3, it may be observed that 2 or 3 pulses will limit the errors in the peak temperatures to less than about 2%. While errors in the temperatures at the start of the last pulse are slightly larger, they are of minor importance insofar as damage is concerned. Moreover errors associated with indepth temperatures and two-dimensional heat transfer will be less than the values indicated above.

To follow transient changes in the damage, about 10 groups should be adequate to represent 100 or more pulses. Less groups should be used with shorter pulse trains. Remaining pulses should be placed at the end of the pulse train and treated individually.

PROGRAMMING

This method requires accurate temperature predictions during and immediately following selected pulses. The selected pulses should be spaced at regular intervals along the length of the pulse train. At least one pulse should be preserved prior to each of the selected pulse or pulses. All other pulses are represented by the mean laser power distributed uniformly with respect to time from one pulse to the next.

TABLE B-1. RATIOS OF APPROXIMATE TO EXACT SURFACE TEMPERATURE RISES ($\tau/\tau_o = 0.1$)

Number of pulses[a]		Temperature ratios		Number of pulses[a]		Temperature ratios	
n_1	n_2	Start of last pulse	End of last pulse	n_1	n_2	Start of last pulse	End of last pulse
10	1	1.247	1.067	100	1	1.072	1.034
10	2	1.053	1.023	100	2	1.020	1.014
10	3	1.032	1.015	100	3	1.014	1.010
10	4	1.022	1.010	100	4	1.011	1.008
10	5	1.016	1.008	100	5	1.009	1.007
25	1	1.150	1.054	400	1	1.036	1.019
25	2	1.037	1.021	400	2	1.010	1.009
25	3	1.024	1.014	400	3	1.007	1.006
25	4	1.018	1.011	400	4	1.006	1.005
25	5	1.015	1.009	400	5	1.005	1.004
50	1	1.104	1.044	900	1	1.024	1.014
50	2	1.028	1.018	900	2	1.007	1.006
50	3	1.019	1.012	900	3	1.005	1.004
50	4	1.015	1.010	900	4	1.004	1.004
50	5	1.012	1.008	900	5	1.004	1.003

[a] $n_1 + n_2$ = total number of pulses considered

n_1 = rumber represented by mean flux in approximate solution

n_2 = number of pulses treated individually at end of pulse train

TABLE B-2. RATIOS OF APPROXIMATE TO EXACT SURFACE TEMPERATURE RISES ($\tau/\tau_o = 0.001$)

Number of pulses[a]		Temperature ratios		Number of pulses[a]		Temperature ratios	
n_1	n_2	Start of last pulse	End of last pulse	n_1	n_2	Start of last pulse	End of last pulse
10	1	1.260	1.018	100	1	1.076	1.017
10	2	1.058	1.005	100	2	1.022	1.005
10	3	1.035	1.003	100	3	1.015	1.004
10	4	1.024	1.002	100	4	1.012	1.003
10	5	1.018	1.002	100	5	1.010	1.002
25	1	1.157	1.018	400	1	1.037	1.004
25	2	1.041	1.005	400	2	1.011	1.003
25	3	1.027	1.003	400	3	1.009	1.003
25	4	1.020	1.003	400	4	1.007	1.002
25	5	1.016	1.002	400	5	1.006	1.002
50	1	1.109	1.018	900	1	1.025	1.011
50	2	1.030	1.005	900	2	1.008	1.004
50	3	1.021	1.004	900	3	1.006	1.003
50	4	1.016	1.003	900	4	1.005	1.002
50	5	1.013	1.002	900	5	1.004	1.002

[a] $n_1 + n_2$ = total number of pulses considered

n_1 = number represented by mean flux in approximate solution

n_2 = number of pulses treated individually at end of pulse train

TABLE B-3. RATIOS OF APPROXIMATE TO EXACT SURFACE TEMPERATURE RISES ($\tau/\tau_o = 0.0001$)

Number of pulses[a]		Temperature ratios		Number of pulses[a]		Temperature ratios	
n_1	n_2	Start of last pulse	End of last pulse	n_1	n_2	Start of last pulse	End of last pulse
10	1	1.260	1.002	100	1	1.076	1.002
10	2	1.058	1.001	100	2	1.022	1.001
10	3	1.035	1.000	100	3	1.015	1.000
10	4	1.024	1.000	100	4	1.012	1.000
10	5	1.018	1.000	100	5	1.010	1.000
25	1	1.158	1.002	400	1	1.037	1.002
25	2	1.041	1.001	400	2	1.011	1.001
25	3	1.027	1.000	400	3	1.008	1.001
25	4	1.020	1.000	400	4	1.007	1.000
25	5	1.016	1.000	400	5	1.006	1.000
50	1	1.109	1.002	900	1	1.025	1.002
50	2	1.030	1.001	900	2	1.008	1.001
50	3	1.021	1.000	900	3	1.006	1.001
50	4	1.016	1.000	900	4	1.005	1.000
50	5	1.013	1.000	900	5	1.004	1.000

[a] $n_1 + n_2$ = total number of pulses considered

n_1 = number represented by mean flux in approximate solution

n_2 = number of pulses treated individually at end of pulse train

To illustrate the method we shall consider a train of 40 pulses. Six series of consecutive pulses shall be replaced by the mean power as illustrated by the squat areas of Figure B-2. Number of pulses eliminated are presented over the shaded areas. The beam power associated with individual pulses obviously exceeds the mean power as indicated by the figure. Pulses yielding accurate temperatures are blackened. At least one pulse should precede each of these pulses to fully develop temperature transients.

Table B-4 indicates the values needed for the arrays NPG(L) and NPR(L) to structure the train as shown in Figure B-2.

TABLE B-4. PROGRAMMING "MEAN POWERS" INTO NONCODED PULSE TRAINS

L	NPG(L)	NPR(L)	L	NPG(L)	NPR(L)
1	2	0	12	1	7
2	1	0	13	5	0
3	1	7	14	1	0
4	5	0	15	1	7
5	1	0	16	3	0
6	1	7	17	1	0
7	5	0	18	1	2
8	1	0	19	1	1
9	1	7	20	1	1
10	5	0	21	1	1
11	1	0			
				40	40

The index L indicates the order in which individual pulses or mean powers are to be considered. The array NPG(L) represents both the number of pulses and how they are to be treated. For normal treatment of pulses, NPG(L) is set equal to 1. NPG(L) values greater than 1 will result in replacement of the pulses by the mean laser power as shown in Figure B-2.

The array NPR(L) should be set equal to zero except for the selected pulses. For the selected pulses, NPR(L) is equal to the number of pulses represented by the pulse. For example, the first "selected" pulse of Figure B-2, shown as black, has an L value of 3. It represents 7 pulses, three preceding it and three in the series of 5 pulses following it. This is also true for the selected pulses with L values of 6, 9, 12, and 15.

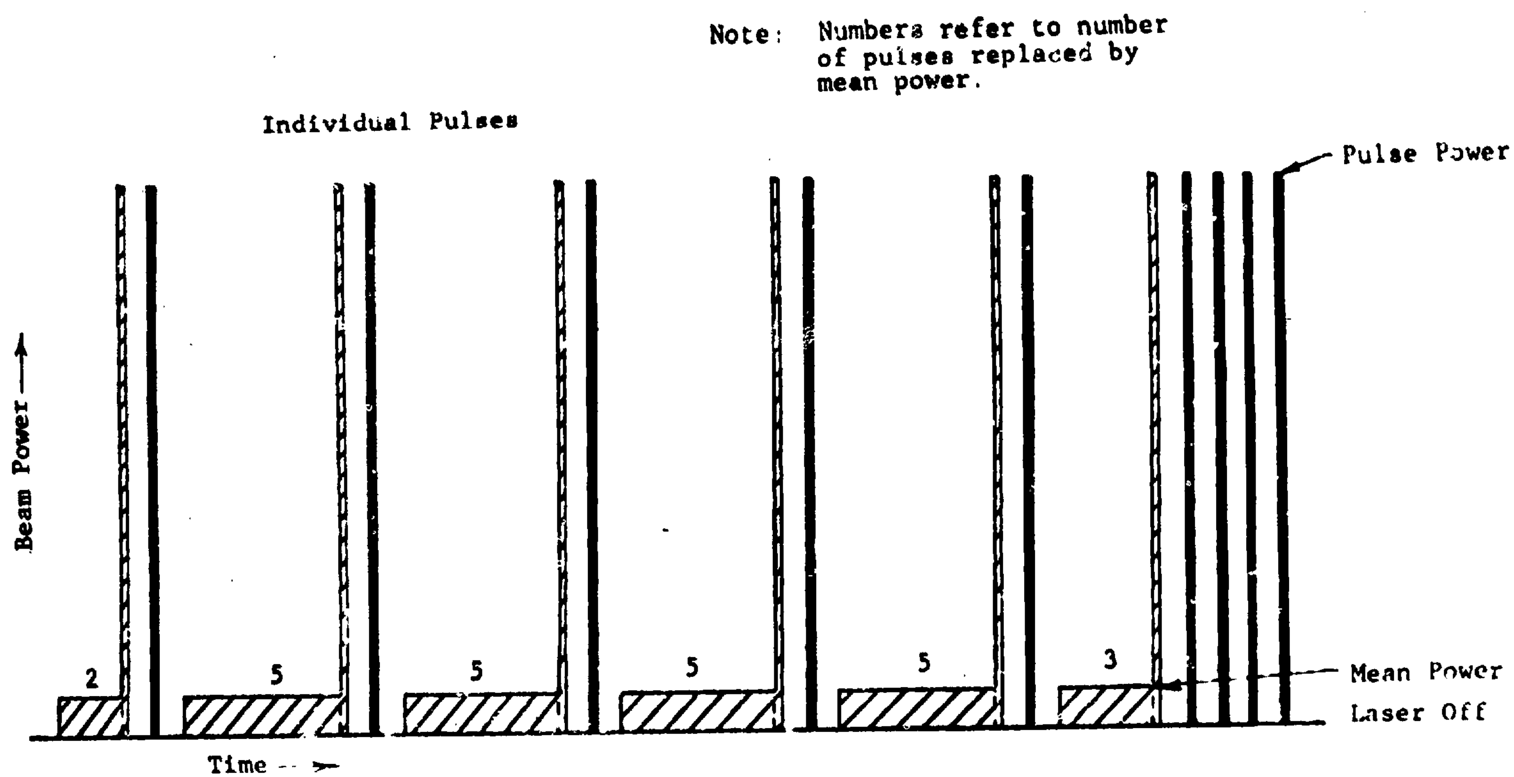

Figure B-2. Structuring pulse train (40 pulses) using mean power to conserve execution time.

APPENDIX C

SKIN MODEL

INTRODUCTION

The skin model consists of a main program plus the 8 subroutines listed below:

- TIME that computes the time steps and associated laser powers
- GRID that computes the grid increments (radial and axial)
- PROF that computes the laser intensities at each of the radial grid points determined by GRID
- CWATER that computes the thermal conductivities and volumetric heat capacities at each of the grid points in terms of variable water content in the tissues
- BA that computes the matrix elements needed to assess the temperature rises
- HTDEP that computes the rates of energy deposition per unit volume of tissue at each of the grid points
- TEMP that uses the alternating explicit-implicit finite-difference technique of the CORNEAL MODEL to compute temperatures allowing for
  - heat losses to the environment
  - heat losses due to blood flow
  - heat losses due to transforming water into steam
  - steam blisters
- DAMAGE that computes the cumulative thermal damage at each of the grid points as well as internal pressures created by superheated water

Code listings, nomenclature, and sample runs are presented at the rear of this appendix.

A flow diagram of the major code routines is shown in Figure C-1. All routines are used during the first time step. Thereafter only the main program and subroutines TEMP and DAMAGE are used unless water losses or irreversible damage have not occurred. If water losses occur during the previous time step, subroutines CWATER and BA are reentered to reevaluate thermal properties and matrix elements. Control is exercised via the parameter IMAX which indicates the maximum depth Z(IMAX) over which water has been lost during the previous time step. During the first time step IMAX is set equal to M (the number of axial intervals) to ensure subroutine CWATER is entered.

When irreversible damage occurs, subroutine HTDEP is reentered to reevaluate the rates of heat deposition using the absorption coefficients of damaged tissue. Here the parameter LMI is used for purposes of entry. During the first time step it equals N. Thereafter LMI indicates the maximum depth (Z(LMI)) of irreversible damage.

In the remainder of this appendix we shall describe the code according to the listing presented at the rear of this appendix. Statement numbers are in sequence in each routine. We shall use these statement numbers for reference purposes. For example, 5.2 would be used to indicate the second line following statement 5. Detailed information required to operate the code are presented in the User's Manual.

Nomenclature describing the variables to be discussed is presented at the rear of this appendix in alphabetical order. Variables followed by dots are read into the code as input data.

DESCRIPTION OF COMPUTER PROGRAM

Main Program

This portion of the code performs the following functions

- reads input data
- calculates the DR and DZ increments along with the maximum radius RN and the maximum depth ZM
- controls course of calculations

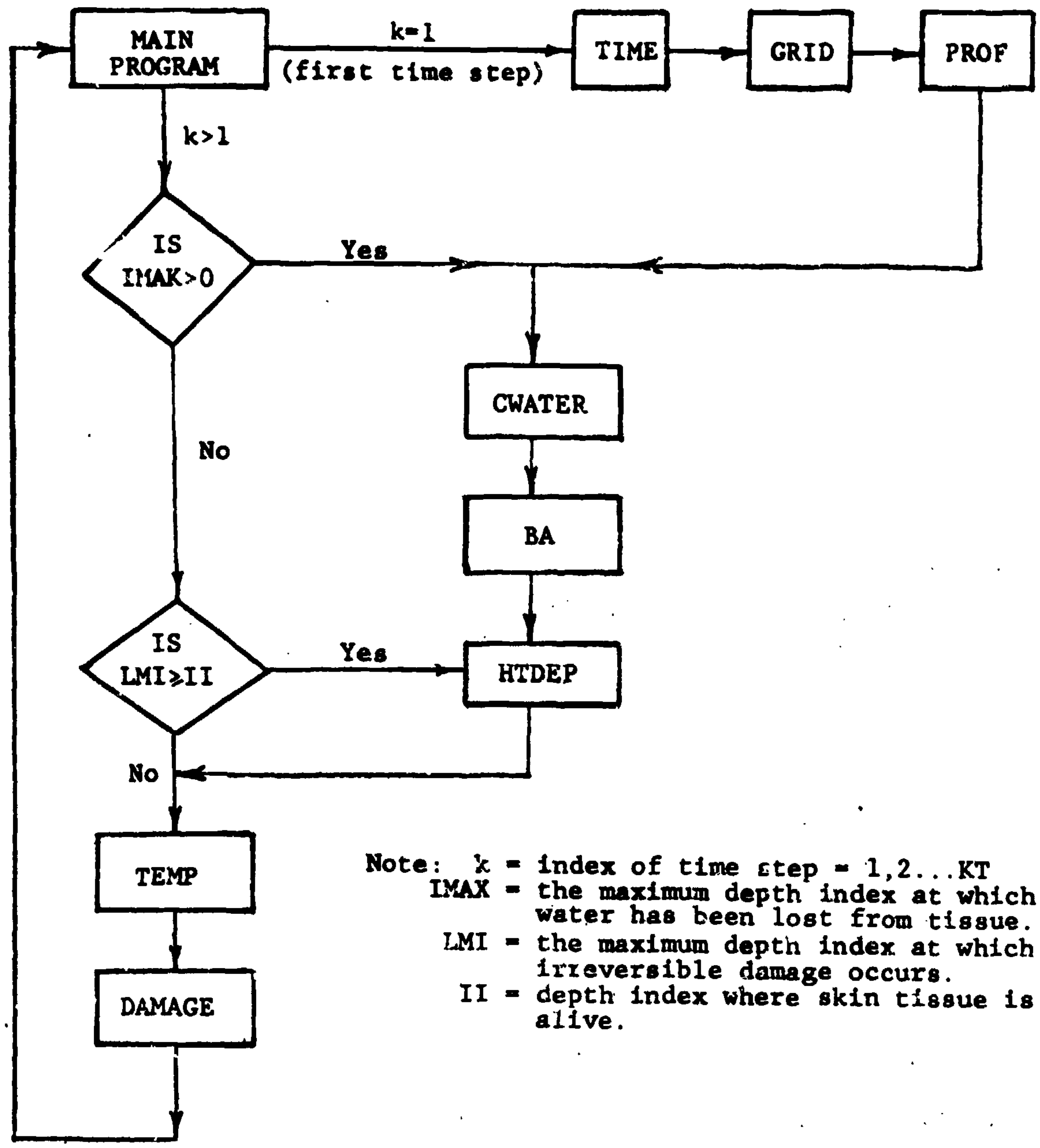

Figure C-1. Flow diagram of skin model.

- prints input data, temperatures, damage, and peak pressure caused by superheated water

- interpolates extent of irreversible damage (radial and axial)

- computes degree of burn

Data cards are read in sequence according to the numbers shown in columns 73-80 of the listing. Numbers followed by letters indicate the particular cards needed. For example with uniform beam profiles one should use card (12, UNIF) and not cards (12, GAUSS) and (12, IRREG). The latter cards are for gaussian and irregular profiles, respectively.

With single-pulse exposures card 14,NC,1 is needed. Card 14,NC,X is needed for pulse trains.

If the pulse train consists of uniform pulses (non-coded) and is to be treated on a pulse-by-pulse basis, no additional cards 14, ... are needed. Otherwise cards (14, NC,GP) are required to group the noncoded pulses.

Coded pulse trains require cards labeled 14,CODED.

Statements 7.2-7.4--Here the heat-transfer coefficient H is set equal to that for dry surfaces unless a sweat layer is present. The value 0.0001 cm represents an arbitrarily small sweat thickness below which sweat is neglected.

Statements 7.3-9.3--These statements are used only if sweat is considered. The arrays TH, ABS, TB, and BI are adjusted to allow for the depth of sweat TSWEAT.

Statements 11.1-18.4--This portion of the code computes the radial increment DR and the radial extent X0 of uniform-, gaussian-, and irregular-beam profiles. At statements 12.1 and 12.2, the DR increment is chosen so that the uniform profile ends halfway between the N1-th and (N1+1) increments. This is done so that heat is deposited equally on either side of r_{N1}. Statement 16.2 computes the radius X0 at which gaussian profiles become insignificant. Intensities q of normalized gaussian profiles are described by

$$q = \exp-(2r^2/(\text{SIGMA})^2) \tag{C-1}$$

where r = radius in cm, q = 1 at r = 0, and SIGMA indicates the extent of the profile. Substituting CUT for q and RIM for r and solving for SIGMA yields

$$\text{SIGMA} = \text{RIM}\sqrt{-2/\ln(\text{CUT})} \qquad \text{(C-2)}$$

Thus equation C-1 becomes

$$q = \exp(r^2 \ln(\text{CUT})/(\text{RIM})^2) \qquad \text{(C-3)}$$

As defined, q = CUT at r = RIM. This portion of the code replaces q with an arbitrarily small number exp-5 and solves for a radius r at which the intensities are insignificant.

Statements 22.5, 24.2, and 42.0--These statements compute the duration XX of the laser exposure.

Statements 40.0-41.3--These statements estimate the depth X4 at which the beam intensity is insignificant. This estimate involves choosing a depth at which the intensity is a very small fraction (i.e., exp-8) of that at the surface.

Statements 44.0 and 44.1--These statements estimate the distance X3 over which heat will be conducted during the duration of the exposure, namely XX.

Statement 44.4--Here ZM is set equal to 3 times the sum of the depths X4 and X3 associated with negligible beam intensity and heat conduction, respectively. The factor 3 is greater than 1 to ensure that ZM is beyond the maximum depth sensing heat.

Statement 44.6--Here we have chosen to fit uniform DZ increments within the sweat plus epidermis by setting M1=1. The number 1 is arbitrary. More than 2 increments will appreciably increase execution times with only marginal improvements in accuracy.

Statements 44.7-44.10--These statements adjust the uniform radial grid to accommodate a hair follicle within the first radial increment. The remaining portion of the uniform grid is subdivided into equal increments DR if the depth DHF of the follicle is set equal to any number greater than ZM.

Statement 46.0--Here RN is set equal to 1.5 times the sum of the radii X0 and X3 associated with negligible beam intensity and heat conduction, respectively. The factor 1.5 is greater than 1 to ensure that the maximum radius RN extends beyond the region heated.

Statements 86.3-86.5--The indices IMAX and LMI are set equal to M so that all subroutines are called prior to the first time step. JMAX is set equal to N to ensure all j values are used in subroutines CWATER and BA.

Statements 86.6-88.4--These statements

- establish the first grid point z_{II} within "live tissues"
- establish the first grid point z_{IP} within the region in which water may become superheated
- initialize ZB5, RGV, IB, RB, V, VO, KK and index of time steps k.

Statements 90.0-90.2--Here the time step DT and laser power POW are set equal to the values computed in subroutine TIME and the elapsed time TTIME is adjusted accordingly.

Statements 90.3-90.5--Subroutines CWATER, BA, HTDEP are called prior to the first time step and following time steps during which water has been lost (IMAX > 0) or damage has occurred (LMI $\geq$ II). Subroutines CWATER and BA revise the thermal properties and matrix elements for water losses, respectively. Subroutine HTDEP alters deposition rates when irreversible damage occurs. The latter is accomplished by replacing the absorption coefficients at the particular grid points with the coefficients for damaged tissue.

Statements 106.4-119.0--These statements have to do with printing temperature rises. Temperatures are printed at intermediate time steps only when the following three conditions are satisfied

- XP(K) equals 1.1. Otherwise the temperatures are too approximate for printing in that either a mean power is being used to represent a group of pulses or the pulse following the mean power.
- time TTIME is between a specified pair of times TIME1(KK) and TIME2(KK). This provision is provided to control periods over which printouts are desired. If one wished printouts at all times, set KX = 1; TIME1(1) = 0; and TIME2(1) to a value several times larger than the duration of the exposure. Extremely large values will cause no problem.

- ITYPEX must be greater or equal to the specified value ITYPE. Here printouts will be provided at every time step if ITYPE is set equal to 1, at every other time step of ITYPE equals 2, etc.

Temperatures and damage are always printed following the last time step.

Statement 119.1--This statement stores the peak temperature at (r_1, z_1) in ZB5. This temperature is used to predict fifth-degree burns following completion of the temperature/damage calculations.

Statements 119.2-119.3--Here the time index k is increased by 1, and the calculations are continued provided k does not exceed the total number of time steps KT. In this regard, the KT time steps include NTX time steps following completion of the exposure. This provision is made to account for the fact that damage continues after the last pulse. For this purpose, NTX should be assigned a reasonably large number, but not so large that KT exceeds the maximum dimension MK allowed in dimensioning arrays. A value such as 20 should suffice. Once damage becomes insignificant, subroutine DAMAGE aborts additional time steps.

Statements 119.4-124.0--At the end of the calculations the cumulative damage is printed for each of the grid points.

Statements 124.1-132.0--Here the peak temperature RB of any superheated water is used to calculate the maximum internal pressure. The resultant pressure represents an upper limit in that it does not allow for tissue deformation, i.e., water remains as water without expansion.

Statements 133.1-154.0--Here the radial and axial extent of irreversible damage is determined by interpolation using the largest radius r_{JDR} and depth z_{IDZ} of irreversible damage found for any of the grid points. The maximum depth is assumed to be on the axis while the maximum radius is assumed to be at the shallowest depth z_{II} of "live" tissue. Only under very unusual heating conditions would these assumptions not be true, i.e., beam profiles with their greatest intensities far removed from the axis. If one encounters such conditions, one considers all i, j values.

In that the same scheme is used to interpolate threshold damage for both coordinates, we shall illustrate the procedure only for r. Damage D is interpolated assuming it decreases exponentially with r in the following fashion.

$$D = D_{JDR} \exp-(X1 \cdot (X2-r_{JDR})) \tag{C-4}$$

Substituting D_{JDR+1} for D and r_{JDR+1} for r, and solving for the constant X1 yields

$$X1 = -\ln(D_{JDR+1}/D_{JDR})/(r_{JDR+1}-r_{JDR}) \tag{C-5}$$

Setting D equal to 1 in equation C-4 and solving for the desired radius X2 yields

$$X2 = r_{JDR} + \ln(D_{JDR})/X1 \tag{C-6}$$

Statements 160.0-162.0--These statements determine the degree of burn LDB. First-, second-, and third-degree burns are based upon the level of damage Ω (see equation 11) at r_1, z_{II}. Fourth-degree burns are indicated if a steam blister forms ($JW > 1$). JW indicates radial extent r_{JW} of a blister and is evaluated at statement 14.1 of subroutine DAMAGE. Fifth-degree burns are predicted if the peak temperature at (r_1, z_1) exceeds DB5.

Subroutine TIME

This subroutine computes and stores the time steps DTX(k). Relatively small time steps are used immediately following the start and end of each pulse. Subsequent time steps are sequentially increased as long as the laser power remains constant (including zero). These periods correspond to the interpulse and intrapulse times.

In addition the code evaluates the array XP(k) which accounts for pulses replaced by mean power. It represents a weight factor which is other than zero only for time steps corresponding to individual pulses yielding accurate temperature predictions. When all the pulses are treated individually, XP(k) = 1 for all time steps, i.e., k = 1 to KT. When pulses have been eliminated, XP(k) will assume values greater than 1 to account for the number of eliminated pulses. XP(k) values are greater than zero only for those time steps DTX(k) yielding accurate temperature predictions.

Initially the arrays POWER(k) and XP(k) are set equal to their most common values, i.e., 0 and 1, respectively. Subsequently, some of these values are revised in the subroutine.

Statements 2.1-2.7--This portion of the code assesses the minimum time step DTO needed for accurate predictions of temperature. The criterion is of the same form as used with explicit-finite differences. The factor ZR is an input parameter and should be approximately 0.5.

Statements 2.12-30.1--This portion of the code computes the time steps DTX(k) and associated arrays POWER(k) and XP(k) for single-pulse exposures.

To ensure accurate damage calculations, a minimum of NTP time steps are used to embrace the pulse duration DPULSE. Statements 2.14-2.17 use a series of uniform time steps DT1 if DT1 is less than or equal to DTO. Otherwise the following series of increasing time step is considered.

$$DTO(1+XC+(XC)^2+ \ldots (XC)^{L1-1}) = DTO \frac{(XC^{L1}-1)}{XC-1} \qquad \text{(C-7)}$$

where the number of terms L1 is chosen so that

$$DTO(XC)^{L1-1} \leq DT1 \qquad \text{(C-8)}$$

This series is used provided that it does not exceed DPULSE. Any residual time is subdivided into equal time steps less than DTO. If the series exceeds DPULSE then the factor R3 is determined such that

$$DTO(1+R3+(R3)^2 \ldots (R3)^{L1-1}) = DPULSE \qquad \text{(C-9)}$$

This is accomplished by rewriting equation C-9 as follows

$$R3 = \exp(\ln(\frac{DPULSE(R3-1)}{DTO} + 1)/L1) \qquad \text{(C-10)}$$

Trial values (X1) are then substituted for R3 on the right-hand side of equation C-10 and solved for R3. If R3 does not agree with X1, X1 is set equal to R3 and the process repeated until they do agree. Usually only a few trials are needed.

During each time step within DPULSE, POWER(k) is set equal to the actual laser power POWX.

Statements 29.0-30.1 compute the NTX time steps following the pulse. The first of these time steps is DTO followed by (XC)DTO, $(XC)^2$DTO, etc. Then the total number of time steps k is stored KT.

Statements 31.0-50.0--This portion of the subroutine computes the arrays DTX(k), POWER(k), and XP(k) for non-coded pulse trains. Statements 31.9 through 38.2 deal with individual pulses while statements 38.3 through 48.1 deal with the mean laser power XX3 used to represent various groups of pulses. The array NPG(L) equals 1 for individual pulses. When a group of pulses is replaced by the mean power, NPG(L) equals the number of pulses in the group.

Following each pulse or group of pulses, the time step DTO is increased by the specified factor ZZ. Usually one should set ZZ = 1. To conserve on computation time, try ZZ values several percent larger than 1. Reduce ZZ closer to 1 if any temperature oscillations occur.

Statements 31.9 and 31.10 compute the number of time steps NP needed to embrace the pulse. The number of time steps is never allowed to fall below 2. Immediately thereafter the time steps DTX(k) are set equal to the constant value XX1, and POWER(k) and XP(k) set equal to POWX and NPR(L), respectively. The array NPR(L) equals the number of pulses represented by individual pulses, and equals 1 when all pulses are treated individually.

Statements 32.3 through 38.0 compute time steps between pulses. Here XX4 represents the first of two expanded time steps, XX4 and XX4(XC), needed to embrace the interpulse time XX2. These time steps are used if XX4 is less than or equal to DTO. Otherwise, the number L1 of expanded time steps needed to exceed XX2 is evaluated at statement 36.0. This is achieved by solving equation C-11 for L1 and dropping the decimal.

$$\frac{(XC^{L1-1}-1)DTO}{XC-1} = XX2 \qquad \text{(C-11)}$$

Then the smallest time step DT2 is evaluated by replacing DTO of equation C-11 with DT2 and solving for DT2. The result is the following L1 time steps:

$$DT2,\ DT2(XC),\ DT2(XC)^2 \cdots DT2(XC)^{L1-1} \qquad \text{(C-12)}$$

The array DTX(k) is set equal to these time steps between statements 36.2 and 38.0.

Statements from 38.1 through 48.1 deal with groups of pulses. The duration X2 of the group of pulses is evaluated at statement 40.0. If X2 is less than DTO, one time step is used. Otherwise, the time steps are computed between statements 46.0 and 48.0 using the same procedure of statements 36.0 and 38.0.

Statements 50.1-54.1--This portion of the code computes NTX time steps following the end of the pulse train. These steps start with DTO followed by DTO(XC), $DTO(XC)^2$, etc.

Statements 70.0-100.0--This portion of the subroutine computes the time steps for coded pulses. The procedure is identical to that used for single pulses between statements 2.12 and 28.0. The only difference is in the pulse durations and number of pulses.

Statements 100.1, 110.1--Here NTX time steps are added onto the end of the coded pulses in the same fashion used with noncoded pulses.

Statements 120.0-121.1--If the total number of time steps exceeds the number MK allocated in dimensioning of arrays, the subroutine will indicate this fact and stop further computations. MK must be ≤ 200.

Subroutine GRID

This subroutine locates the grid points based upon the

- values selected for N1, N, and M
- M1, DR, DZ, RN, and ZM values computed in the main program
- diameter SHF and depth DHF of hair follicle

A hair follicle is considered only if it lies at a depth less than the maximum depth ZM (DHF < ZM). A typical grid system without a hair follicle is shown in Figure A-1 presented on page 61.

Statements to 10.3--Following the last uniform DR, the radial increments are expanded by the factor R2 chosen so CK increments exist between (RN-CP) and RN. This requires that

$$DR\frac{(R2)^{CK}-1}{R2-1} = CP \qquad (C-13)$$

R2 is determined by rewriting equation C-13 as follows

$$R2 = \exp(\ln(\frac{CP\ (R2-1)}{DR} + 1)/CK) \qquad (C-14)$$

This equation is solved for R2 in the same fashion described in solving equation C-10.

Statements 13.0-15.0--Here the first N1+1 = N4 grid points R(j) are determined for the uniform portion of the radial grid. When a hair follicle is present, the first increment equals half the diameter SHF of the follicle. The next N1-1 increments DR are uniform.

Statements 15.1-16.0--Here the factor R2 is used to evaluate the grid points R(j) over the expanded portion of the radial grid.

Statements 16.1-18.0--Here the first M1+1 = M4 grid points Z(i) are computed over the uniform portion of the axial grid.

Statements 18.5-26.0--These statements assume no hair follicle. They evaluate the grid points Z(i) over the expanded portion of the axial grid. The technique is the same as that used for the radial grid.

Statement 30.0--To accommodate a hair follicle, it is necessary to commence to contract the axial grid points early in the expansion phase to achieve an increment having dimensions identical to the follicle. Thereafter the increments are expanded to ZM.

Statement 30.0 partitions the M-M1 increments for the expansion phases.

Statements 30.1-36.0--Here the first LX increments following the uniform grid are expanded to a depth roughly midway between the base of the epidermis and the follicle.

Statements 36.1-46.0--The next LX-1 increments are contracted to the follicle, with the last increment equal to the follicle diameter SHF. The follicle is centered at Z(L2). One additional increment, Δz = SHF, is provided beneath the follicle.

Statements 47.0-62.0--Finally the remaining M-L2-1 increments are expanded to ZM.

Statements 70.0-72.0--This portion of the subroutine assesses the index IW associated with Z(IW) nearest ZBL. ZBL represents the depth at which blisters form and should be set equal to the thickness of the epidermis in inputing data.

Subroutine PROF

This subroutine computes the profile HR(j) of the laser beam in terms of the intensity of the incoming beam. Three radially symmetric profiles are considered, namely

- Irregular profiles--whose shape is described on a point-by-point basis using the arrays PX(L) and RX(L)
- Gaussian profiles--whose shape is described in terms of intensity CUT for normalized profiles at radius RIM
- Uniform profiles--which have a constant intensity over a radius RUNIF and zero intensity thereafter

The radius RU of the grid work is selected in the main program so that it extends well beyond the profile.

Input data describe the shape of the profiles. Intensities are adjusted to yield 1 watt of beam power using the factor QP. Actual beam powers are introduced in subroutine TEMP.

<u>Statements 11.6-18.1</u>--This portion of the subroutine computes the factor QP for irregular profiles. The profile is linearly interpolated between points using

$$p(r) = PX(L-1) + \frac{r - RX(L-1)}{RX(L) - RX(L-1)}(PX(L)-PX(L-1)) \quad \text{(C-15)}$$

where p(r) represents the value of PX at r.

The term X5 in the listing represents the integral of p(r) with respect to radial area over the entire profile. X5 is determined by integrating between successive pairs of points RX(L-1) and RX(L) as follows

$$\int_{RX(L-1)}^{RX(L)} p(r)2\pi r dr \quad \text{(C-16)}$$

Results are stored in X5. QP is then computed allowing for energy losses due to hairs and reflection.

Statements 18.2-23.0--Here the irregular profile is interpolated at radial increments RINT starting at $r = 0$ using equation C-15. Results are stored in FX(L).

Statements 23.1-34.0--This portion of the subroutine computes the radial area FA(L) and power FP(L) between $r = 0$ and $r = (L-.5)$RINT. Small values are used for RINT, consistent with accurate integration.

Statements 34.1-35.0--Here the values of FA and FP are determined at radii midway between successive radial grid points R(j). Increments of FP are then divided by increments of FA and multiplied by QP to arrive at HR(j) for irregular profiles.

Statements 44.0-47.0--Gaussian profiles have the following shape

$$\exp-(2r^2/(\mathrm{SIGMA})^2) \qquad \text{(C-17)}$$

This expression is normalized so that it equals 1 at $r = 0$. Input data indicate its value, CUT, at the specified radius RIM. If one chooses a value of $1/e^2$ for CUT then r = SIGMA.

Setting the above expression equal to CUT and replacing r with RIM yields

$$\mathrm{SIGMA} = \mathrm{RIM}\sqrt{-2/\ln(\mathrm{CUT})} \qquad \text{(C-18)}$$

Multiplying equation C-17 by $2\pi r$ and integrating over all r yields $\pi(\mathrm{SIGMA})^2/2$. This result is then used to compute the QP value given by statement 46.1.

Statements 59.0-72.0--Uniform profiles are considered to be of unit magnitude, and to extend to the specified radius RUNIF. The integral of such profiles with respect to radial area is simply $\pi(\mathrm{RUNIF})^2$ and yields the QP value cited at statement 59.0.

In that r = RUNIF lies midway between R(N1) and R(N1+1), only the first N1 HR(j) values are set equal to QP. All other HR(j) values, with $j = N+1, \ldots N3$ are equal to 0.

Subroutine CWATER

This subroutine assigns values for the blood flows, thermal conductivities and volumetric heat capacities to the grid points. Blood flows remain constant with respect to time. Thermal properties are expressed in terms of water content and hence change with water loss.

Statements 6.0-8.2--Blood flows BL(L1) vary with depth by assigning constant values over tissue layers of thicknesses of TB(L1). Blood flows are assigned at each of the depths Z(i) according to the layer in which Z(i) resides.

Statements 8.3-26.0--This section assigns values for the water content WW(i), density DD(i), non-water constituents SS(i), and specific heat CH(i) at the various depths Z(i).

Sweat is considered only if it has a depth greater than the arbitrarily small value of 0.0001 cm. Water content and density are considered constant across the dermis and within subcutaneous tissues. If sweat is absent, water content and density vary linearly across the epidermis starting with values W1 and D1, respectively, at its outer surface, and ending with values W2 and D2 at its base. When sweat is present the values W1 and D1 are replaced by those for sweat, namely W0 and D0.

Equations used to calculate specific heat and the thermal conductivities are presented in the section "Thermal Properties of Skin."

Statements 26.3-33.0--This portion of the subroutine assigns values for water content, heat capacity, and thermal conductivity to each of the grid points.

Statements 40.0-44.0--Whenever water losses occur, the water content WATER(i,j) is adjusted in subroutine TEMP. Then this portion of the subroutine is used to revise the heat capacities and thermal conductivities at the affected grid points, i = 1, IMAX and j = 1, JMAX.

Subroutine BA

Subroutine BA computes the matrix elements A1(i,j), A2(i,j), A3(i,j), B1(i,j), B2(i,j) and B3(i,j). These matrix elements are described in Appendix A.

Statements to 11.0--This section computes the arrays presented by equations A-26 to A-29 and A-31 to A-34.

Statements 12.0-26.0--The matrix elements are evaluated for all grid points except for those incurring no heating, points with i = M3 or j = N3. Thereafter, the matrix elements are revised immediately after any water is lost. These revisions pertain to elements associated with grid points contained within R(JMAX) and Z(IMAX). The indices JMAX and IMAX are determined in subroutine TEMP.

Subroutine HTDEP

Subroutine HTDEP computes the rates of energy deposition S(i,j) per unit volume of tissue at each of the grid points (Z(i), R(j)). This is accomplished by computing the radiant intensities at depths ZH(i) midway between the grid points and using the intensity differences to determine the rates of energy deposition.

Statements 5.1-20.0--First, determinations are made of the radiant intensities at each of the depths ZE(L) at which the absorption coefficients undergo change. Here we start with a unit intensity (IE(1) = 1) at the surface (ZE(1) = 0) and compute the intensities IE(L) at each of the depths ZE(L). The depths ZE(L) of interest are

$$\mathrm{ZE(L)} = \sum_{\ell=1}^{L=1} \mathrm{TH}(\ell) \qquad \text{(C-19)}$$

The intensities at these depths are

$$\mathrm{IE(1)} = 1$$
$$\mathrm{IE(2)} = \mathrm{IE(1)exp(-ABS(1)\cdot TH(1))}$$
$$\vdots$$
$$\mathrm{IE(LZ+1)} = \mathrm{IE(LZ)exp(-ABS(LZ)\cdot TH(LZ))} \qquad \text{(C-20)}$$

These computations are conducted between statements 5.1 and 12.0.

The next step is to use the above intensities IE(L) to determine the intensities IZ(i) at the depth ZH(i). At the surface, IZ(1) equals 1. Otherwise

$$\mathrm{IZ(i+1)} = \mathrm{IE(L)exp(-ABS(L)(ZH(i)-ZE(L))} \qquad \text{(C-21)}$$

where the index L is such that

$$\mathrm{ZE(L)} < \mathrm{ZH(i)} < \mathrm{ZE(L+1)} \qquad \text{(C-22)}$$

Heat deposition rates are computed between statements 16.3 and 20.0. This computation is accomplished by dividing the difference of successive pairs of IZ(i) by the distance between the corresponding depths ZH(i), and multiplying by HR(j).

Statements 20.2-22.1--This portion of the subroutine is entered only if a hair follicle is considered. The follicle is at depth Z(IHF) between radii r = 0 and r = R(2), and is considered opaque.

Statements 32.0-42.0--Whenever irreversible damage occurs, the code adjusts the rates of heat deposition associated with grid points within the damage radius R(LNJ).

Here LXX represents the largest index to be considered. It equals the maximum i index associated with heat deposition and damage. First, all S(i,j) of concern are initialized to zero.

Of interest are grid points within the maximum depth Z(LMI) of damage. In that some of the tissues may be undamaged, it is necessary to allow for both damaged and undamaged tissues. From statements 34.1 to 36.0 the radiant intensity is computed for each depth ZH(i) by multiplying the intensity at the prior depth ZH(i-1) by one of the following factors:

$$\text{damaged tissues: } \exp-[(\mathrm{ABSC})(\mathrm{ZH}(i)-\mathrm{ZH}(i-1))] \tag{C-23}$$

$$\text{undamaged tissues: } \mathrm{IZ}(i)/\mathrm{IZ}(i-1) \tag{C-24}$$

The remaining computations are similar to that described for statement 20.0.

Statements 36.1 through 37.0 concern undamaged tissues and follow the same procedure described above.

Statements 42.1-44.1--Here the energy is entirely absorbed by the hair follicle, so no energy is deposited directly below the follicle.

Subroutine TEMP

This subroutine performs the following functions:

- computes transient temperatures allowing for steam generation
- adjusts water content WATER(i,j) for any water loss
- computes maximum temperatures at (R(1), Z(1)), of hair follicle, and of all grid points

If mean laser powers are used and boiling commences, this subroutine treats remaining pulses individually by reevaluating the arrays DTX(k), POWER(k), and XP(k) for future time steps k.

Statements to 2.3--On each entry of the subroutine, IMAX is set equal to zero to account for the fact that boiling may cease between pulses and certainly after the exposure. Remaining statements in this section initialize various arrays and parameters.

Statements 3.0-4.1--The previous temperatures V(i,j) are preserved VO(i,j) for reuse in successively approximating the rates of heat loss in transforming water into steam. After each trial the resultant V values are returned to VO. Here KW (number of trials) is initialized to 0.

Statements 9.0-48.7, 50.0--This portion of the subroutine computes the temperatures using half time steps DT/2 for COLUMN and half time steps DT/2 for ROW. Except for indices, the COLUMN computations are of identical form as those for ROW discussed in Appendix A. Statements 9.1-44.0 for COLUMN and 45.3-48.0 for ROW evaluate the terms D, E, F, and G of Appendix A. In this subroutine the terms DXC and DXR correspond with D; CXC and CXR with E; FXC and FXR with F; and SUM with G. Rates of heat deposition are described by POWS(i,j) and rates of heat losses due to steam formation by SW(i,j).

Statements 44.1-45.0 for COLUMN, and statements 48.0-48.5 plus 50.0 for ROW evaluate the temperatures using the above arrays. The equations for ROW are those of equation A-39 of Appendix A.

Statements 48.6-4811, 50.1, 50.2--This portion of the code evaluates the i and j indices IMAX and JM(i) describing the region over which water is lost. These evaluations are made with all SW(i,j) values set equal to zero. Temperature computations are completed if none of the grid points (i = 1 to IP) with available water exceeds the temperature of boiling water. Otherwise, KW is increased to 1 and a trial and error method is used to determine the SW(i,j) values needed to reduce the temperatures to that of boiling.

Statements 50.3-57.0--Two techniques are used to determine SW(i,j) by successive approximations. These techniques will be labeled 1 and 2. Technique 1 perturbs the previous SW(i,j) values as follows

$$SW(i,j) \rightarrow SW(i,j) + ZW(KW)(V(i,j) - XW)VSH(i,j)/DT. \qquad (C-25)$$

Here the array ZW(KW) is inputed by the user and should have values of about 1 to 1.5. The most recent temperatures are V while the previous temperatures are VS. This technique works best when

1) most of the absorbed heat remains in the particular grid increments during the time step

2) SW(i,j) corrections are relatively small

Statement 50.8 determines whether or not condition 1 is true. If it is true, JSW(i,j) is set equal to 1. Otherwise, it is equal to 0. Condition 2 is judged by comparing the most recent temperature changes with the arbitrarily small temperature difference of 1°C. Technique 1 always is called for the first of the NW trials and for trials KW = IKW to NW.

The second technique alters previous SW(i,j) values by large amounts and is important in rapidly achieving SW values of the correct magnitude, but it is not as good as technique 1 in making small refinements. Technique 2 involves using the previous SW(i,j) correction divided by the resulting V(i,j) changes. The ratio is multiplied by the desired temperature change XW-V(i,j) and the factor ZW(KW) to arrive at subsequent changes of SW(i,j). If the resulting SW correction is less than that described by equation C-25, equation C-25 is used in that it provides more accurate estimates whenever the revisions are small.

<u>Statements 57.1-57.2</u>--These statements prevent SW values from becoming negative or exceeding values allowed by the amount of available water.

<u>Statements 57.3-62.1</u>--Here the change in SW(i,j) is stored in ZSW(i,j) and the most recent temperatures V(i,j) are stored in VS(i,j).

Statements 60.4-62.1 reset the V(i,j) values back to their original values before directing the code to statement 9.0 for the next of the NW trials.

<u>Statements 63.0-70.1</u>--This portion of the subroutine is entered after completing the NW trials. It performs the following functions

- subtracts water losses from WATER(i,j)
- reinitializes the arrays SW(i,j), JSW(i,j), and JM(i)
- determines the maximum radius R(JMAX) over which water has been lost.

The next section is entered if some of the pulses have been grouped together to conserve on computational time.

Statements 70.2-84.2--It is not valid to treat pulses using a mean power once steam commences to be generated. In such situations it is necessary to treat the remaining pulses individually. To accomplish this, the subroutine recomputes the arrays DTX(k), POWER(k), and XP(k) for individual pulses. The method is identical to that described in subroutine TIME for noncoded pulse trains.

Statements 70.3-74.0 determined the

- number of pulses that have been treated, L1
- number of pulses remaining
- minimum time step DTO
- initialize POWER(k) and XP(k) for remaining pulses
- evaluate the parameters XX2, XX4, XX5, and XX6 used in subroutine TIME
- sets the variable time index LK equal to k
- directs the subroutine to statement 82 once all KP remaining pulses have been treated

Statements 74.1-78.1 compute the time steps between pulses. These statements are identical to statements 32.1-38.2 of subroutine TIME except for omitting the array XP(k), and the use of KO and LK for k and L3, respectively.

Statements 79.0-80.1 evaluate time steps during pulses. The same procedure is used as described for statements 31.6-32.1 of subroutine TIME. The array NPG(L) is omitted in that all remaining pulses are treated individually.

Statement 80.2 reduces the remainir [illegible] s KP to be
treated by 1. Then the subroutine che [illegible] if suffi-
cient storage is available for the n [illegible] ere LK
represents the number of time steps [illegible] repre-
sents the number of time steps nee [illegible] pulse,
and NTX equals the number of time [illegible] llowing
the last pulse. If the number of [illegible] than
the allotted storage MK, the subr [illegible] r the
next pulse. Otherwise it will ir [illegible] ent
storage is not available, abort [illegible] and
indicate the number of pulses [illegible] orte

Statements 82.0-84.1 compute the time steps following the last pulse. The procedure is identical to that performed in time. NGX is set to zero to alert the code to the fact that the pulses are being treated individually and to prevent reentry of this portion of the subroutine.

Statements 90.0-92.1--This section is used following each time step. It sets RGV to the highest temperature exceeding RGV. Also it searches the region in which superheated water may result for peak temperature. The peak temperature and associated depth index i are stored in RB and IB, respectively. Finally, the peak temperature of any hair follicle is stored in VHF.

Subroutine DAMAGE

This subroutine performs the following functions:

- evaluates thermal damage D(i,j) at each of the grid points as well as the radial R(LNJ) and axial Z(LMI) extent of irreversible damage
- revises matrix elements A1, A2, and A3 if a blister forms
- aborts future time steps when damage becomes insignificant

Statements to 4.0--KTO represents the index k associated with the last time step associated with the last pulse and it is used to abort time steps following the last pulse once further damage becomes insignificant.

Statements 4.7-6.4--Damage is computed only if the temperature V exceeds XD, where XD is the lowest temperature at which damage is significant. Damage calculations are also aborted if XP(k) is not an integer value greater than 0. The index LL equals 1 when pulses remain to be treated. This index prevents damage calculations from being aborted until the laser exposure is completed.

Statements 6.6-12.0--Here the indices ID and JD are evaluated. These indices correspond to the depths Z(ID) and R(JD) over which damage is occurring.

Statements 12.1-14.1--This portion of the subroutine compares the temperature of grid points, nearest to the depth ZBL at which blisters form, with the temperature DTEMP associated with blister formation. Matrix elements A1, A2, and A3 are revised if DTEMP is achieved. This involves use of equations A-24 and A-25 presented in Appendix A.

The index JW is used to avoid recalculating the matrix elements.

Statements 14.2-22.0--Here damage is calculated only if the grid points lie within the region of "live tissue," at Z(II) or below. Damage is calculated using stepwise approximations of equation 11. Incremental damage X3 is multiplied by the number of pulses XP(k) being represented.

Statements 20.2 and 20.3 determine the i and j indices (LMI and LNJ) of the radius R(LNJ) and depth Z(LMI) of irreversible damage. These indices are used to alter the absorption coefficient in subroutine HTDEP whenever irreversible damage occurs.

Statement 22.1--This statement aborts additional calculations when damage becomes insignificant. Five time steps are allowed at the end of the last pulse before this condition is exercised. This provision is provided in that the incremental damage X3 of statement 14.13 may be small as a consequence of the small time steps used immediately following a pulse.

CODE DOCUMENTATION

This section provides compute printouts of the following:

- nomenclature used in the code
- code listing
- three sample computer runs with input data cards: a single pulse, multiple noncoded pulses treated in groups, and coded pulses.

Property data used in the sample runs are identical to that used in the section "Pig Experiments".

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```
C *** NOMENCLATURE FOR SKIN MODEL
C     --------------------------
C *** PARAMETERS FOLLOWED BY DOTS REPRESENT INPUT DATA
C      ABS(L),         ABSORPTIVITY OF SKIN ASSOCIATED WITH LAYER TH(L),1/CM
C      ABSC.           ABSORPTIVITY OF IRREVERSIBLY DAMAGED SKIN,1/CM
C      ABSW.           ABSORPTIVITY OF WATER,1/CM
C      ALPHA           THERMAL DIFFUSIVITY,CM2/SEC
C      A1,A2,A3        MATRIX ELEMENTS ASSOCIATED WITH Z FOR TEMPERATURE
C                      CALCULATIONS,CAL/CM3-SEC-C
C      BLOOD(I,J)      BLOOD FLOW AT Z(I),R(I),GM/CM3-SEC
C      BL(L),          BLOOD FLOW IN L-TH LAYER OF THICKNESS TB(L),GM/CM3-SEC
C      B1,B2,B3        MATRIX ELEMENTS ASSOCIATED WITH R FOR TEMPERATURE
C                      CALCULATIONS,CAL/CM3-SEC-C
C      CB.             SPECIFIC HEAT OF BLOOD,CAL/GM-C
C      CH(I)           SPECIFIC HEAT OF SWEAT OR TISSUES AT DEPTH Z(I),
C                      CAL/GM-C
C      CK              NUMBER OF GRID INCREMENTS FROM LAST OF UNIFORM INCRE-
C                      MENTS TO FINAL INCREMENT
C      CON1.,CON2.     CONSTANTS FOR CALCULATING THERMAL CONDUCTIVITIES AS
C                      FUNCTION OF WATER CONTENT,CAL/CM-SEC-C
C      CON(I,J)        THERMAL CONDUCTIVITIES OF SWEAT OR TISSUES AT Z(I),R(J),
C                      CAL/CM-SEC-C
C      CP              DISTANCE FROM BEGINNING OF LAST UNIFORM GRID INCREMENT
C                      TO END OF FINAL INCREMENT,CM
C      CUT.            CONSTANT INDICATING INTENSITY OF GAUSSIAN PROFILE
C                      AT RADIUS RIM CONSIDERING UNIT INTENSITY AT AXIS,
C                      DIMENSIONLESS
C      D(I,J)          CUMMULATIVE THERMAL DAMAGE AT Z(I),R(J),DAMAGE
C                      REVERSIBLE WHEN D(I,J) LESS THAN 1,IRREVERSIBLE WHEN
C                      D(I,J) GREATER THAN 1,DIMENSIONLESS
C      DAM(L,1),       NATURAL LOGS OF COEFFICIENTS OF EXPRESSION FOR RATE OF
C                      THERMAL DAMAGE,TEMPERATURES BELOW 50 C FOR L=1, TEMPER-
C                      ATURES ABOVE 50 C FOR L=2,1/LN(SEC)
C      DAM(L,2),       ARGUMENTS OF EXPONENTIALS OF EXPRESSION FOR RATE OF
C                      THERMAL DAMAGE,TEMPERATURES BELOW 50 C FOR L=1, TEMPER-
C                      ATURES ABOVE 50 C FOR L=2,DEGREES K
C      DB1.            AMOUNT OF DAMAGE NEEDED TO CAUSE FIRST DEGREE BURN,
C                      DIMENSIONLESS
C      DB2.            AMOUNT OF DAMAGE NEEDED TO CAUSE SECOND DEGREE BURN,
C                      DIMENSIONLESS
C      DB5.            TEMPERATURE ABOVE WHICH TISSUES CHAR,C
C      DD(I)           DENSITY AT Z(I),GM/CM3
C      DEPID.          THICKNESS OF *DEAD* EPIDERMAL LAYER,CM
C      DHF.            DEPTH OF HAIR FOLLICLE LOCATED ON BEAM AXIS,CM, WILL
C                      CONSIDER HAIR FOLLICLE ONLY IF DHF IS LESS THAN ZM,
C                      THEREFORE TO OMIT HAIR FOLLICLE SET DHF TO VERY LARGE
C                      NUMBER SUCH AS 1000.
C      DPULSE.         PULSE WIDTH OF NON-CODED PULSES (ALL UNIFORM),SEC
       DPULSC(L).      PULSE WIDTHS OF CODED PULSES, L=1 FOR FIRST PULSE, L=2
C                      FOR SECOND PULSE,ETC., HERE *PULSES* MAY HAVE ANY
C                      POWER FROM 0 AND UP,SEC
C      DR              MINIMUM RADIAL INCREMENT,CM
C      DT              TIME STEP WHICH VARIES WITH INDEX K,SEC
C      DTEMP.          TEMPERATURE OF SUPERHEATED WATER AT WHICH TISSUES ARE
C                      ASSUMED TO SEPARATE,C
C      DTO             MINIMUM TIME STEP,SEC
C      DTX(K)          TIME INTERVALS ASSOCIATED WITH LASER POWERS POWER(K),
C                      SEC
C      DZ              MINIMUM AXIAL INCREMENT,CM
C      D0.,D1.,D2.,    DENSITY OF SWEAT,EPIDERMAL SURFACE,DERMIS,AND SUB-
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C       D3.             CUTANEOUS TISSUES,GM/CM3
C       FA(L)           TOTAL RADIAL AREA FROM R=0 TO (L-.5)*RINT,CM2
C       FP(L)           INTEGRAL OF PX(L) WITH RESPECT TO RADIAL AREA FROM R=0
C                       TO (L-.5)*RINT,CM2
C       FX(L)           INTERPOLATED VALUE OF PX AT (L-1)*RINT,DIMENSIONLESS
C       H               HEAT-TRANSFER COEFFICIENT AT SKIN SURFACE,CAL/CM2-SEC-C
C       H1.             HEAT-TRANSFER COEFFICIENT AT SURFACE(DRY),CAL/CM2-SEC-C
C       H2.             HEAT-TRANSFER COEFFICIENT AT SURFACE(WET),CAL/CM2-SEC-C
C       HAIR.           FRACTION OF RADIATION INTERCEPTED BY HAIRS,DIMENSIONLESS
C       HR(J)           LASER BEAM PROFILE AS FUNCTION OF RADIUS R(J) FOR
C                       LASER POWER OF 1 WATT,CAL/CM2-SEC-WATT
C       HW.             HEAT TRANSFER COEFFICIENT ACROSS STEAM BLISTER,
C                       CAL/CM2-SEC-C
C       I               INDEX OF AXIAL INCREMENTS
C       IB              I INDEX OF DEPTH Z(I) AT WHICH PEAK PRESSURES OCCUR
C       ID              I INDEX OF MAXIMUM DEPTH Z(I) AT WHICH THERMAL DAMAGE
C                       IS OCCURRING, DAMAGE MAY OR MAY NOT BE REVERSIBLE
C       ID1.            MINIMUM I VALUE AT WHICH ARRAYS V(I,J),D(I,J),S(I,J),
C                       ARE PRINTED
C       ID2.            MAXIMUM I VALUE AT WHICH ARRAYS V(I,J),D(I,J),S(I,J),
C                       ARE PRINTED
C       IE(L)           FRACTION OF BEAM INTENSITY AT DEPTH ZE(L),WHERE
C                       IE(1)=1 AT SURFACE CORRESPONDING TO Z(1)=0.,DIMENSION-
C                       LESS
C       INF             I INDEX OF DEPTH Z(INF) OF HAIR FOLLICLE
C       II              I INDEX INDICATING DEPTH OF *LIVE* TISSUES, TISSUES LIVE
C                       FROM Z(II) AND BEYOND
C       II1.,II2.       MINIMUM AND MAXIMUM I INDICES FOR 2 OR 3-D PLOTS
C       II3.            I INDEX TO BE MARKED ON 2 OR 3-D PLOTS
C       IMAX            MAXIMUM I INDICE AT WHICH WATER HAS BEEN LOST
C       IP              I INDEX INDICATING SHALLOWEST DEPTH Z(IP) AT WHICH
C                       STEAM IS CONFINED
C       IPROF.          INDEX INDICATING SHAPE OF LASER PROFILE,=0 UNIFORM,
C                       =1 GAUSSIAN, =2 IRREGULAR
C       ITYPE.          INDEX CONTROLLING FREQUENCY OF PRINTING TEMPERATURES,
C                       FOR ITYPE=1 TEMPERATURES WILL BE PRINTED FOR EACH TIME
C                       STEP BETWEEN TIME INTERVAL FROM TIME1(KK) TO TIME2(KK),
C                       FOR ITYPE=2 EVERY OTHER TIME STEP,ETC.
C       ITYPEX          INDEX USED TO CONTROL FREQUENCY OF PRINTING TEMPERATURES
C       IW              I INDEX OF DEPTH Z(I) NEAREST DEPTH ZBL AT WHICH TISSUES
C                       SEPARATE
C       IZ(I)           FRACTION OF BEAM INTENSITY AT VARIOUS DEPTHS ZH(I-1),
C                       WHERE IZ(1)=1, AT SURFACE,DIMENSIONLESS
C       J               INDEX OF RADIAL INCREMENTS
C       JD              J INDEX OF MAXIMUM RADIUS R(J) AT WHICH THERMAL DAMAGE
C                       IS OCCURRING, DAMAGE MAY OR MAY NOT BE REVERSIBLE
C       JD1.            MINIMUM J VALUE AT WHICH ARRAYS V(I,J),D(I,J),S(I,J),
C                       ARE PRINTED
C       JD2.            MAXIMUM J VALUE AT WHICH ARRAYS V(I,J),D(I,J),S(I,J),
C                       ARE PRINTED
C       JJ1.,JJ2.       MINIMUM AND MAXIMUM J INDICES FOR 2 OR 3-D PLOTS
C       JM(I)           MAXIMUM J INDEX AT WHICH WATER IS LOST FOR I INDICES
C                       LESS THAN IP
C       JMAX            MAXIMUM J INDEX AT WHICH WATER HAS BEEN LOST
C       JW              RADIAL INDEX ASSOCIATED WITH BLISTER FORMATION, =1
C                       IF BLISTER HAS NOT FORMED, OTHERWISE BLISTER EXTENTS
C                       TO RADIAL DISTANCE R(JW)
C       K               INDEX OF TIME STEPS, RANGES FROM 1 TO KT
C       KK              INDEX OF SPECIFIC TIME INTERVAL TIME1(KK) TO TIME2(KK)
C                       TO ASSESS WHETHER OR NOT TEMPERATURES ARE TO BE PRINTED
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C       KO              INDEX OF TIME STEP
C       KP              INDEX OF NUMBER OF PULSES REMAINING TO BE TREATED
C       KT              TOTAL NUMBER OF TIME STEPS TO BE CONSIDERED IN CALCU-
C                       LATIONS
C       KTYPE.          INDEX INDICATING WHETHER OR NOT TO PRINT CARDS FOR 2 OR
C                       3-D PLOTS,KTYPE=1 FOR CARDS,KTYPE=0 FOR NO CARDS
C       KX.             NUMBER OF TIME INTERVALS TIME1(KK) TO TIME2(KK) DURING
C                       WHICH TEMPERATURES ARE TO BE PRINTED,KK=1 TO KX
C       LASER.          INDEX INDICATING WHETHER OR NOT PULSE TRAIN IS CODED,
C                       =1 IF NOT CODED, =2 IF CODED
C       LB.             NUMBER OF LAYERS AT WHICH BLOOD FLOW IS DESCRIBED
C       LDB             HIGHEST DEGREE OF BURN PRODUCED,DIMENSIONLESS
C       LI              NUMBER OF RADIAL INCREMENTS WITH WHICH TO SUBDIVIDE
C                       RADIAL DISTANCE FROM R=0 TO RX(LR)
C       LMI,LNJ         MAXIMUM I AND J INDICES AT WHICH IRREVERSIBLE DAMAGE
C                       OCCURS,INITIALLY LMI SET EQUAL TO M TO ENTER SUBROUTINE
C                       CWATER
C       LR.             NUMBER OF INTENSITIES SPECIFIED IN IRREGULAR PROFILE
C       LW              INDEX CONTROLLING WHETHER OR NOT TO MAINTAIN RATES OF
C                       HEAT LOSS SW FOR NEXT TIME STEP
C       LZ.             NUMBER OF SKIN LAYERS HAVING DIFFERENT OPTICAL ABSORP-
C                       TIVITIES
C       L1,L2,L3...     DUMMY PARAMETERS
C       M.              TOTAL NUMBER OF Z GRID INCREMENTS
C       MK.             MAXIMUM NUMBER OF TIME STEPS TO BE CONSIDERED, SHOULD
C                       NOT EXCEED DIMENSION OF ARRAYS POWER,XP, AND DTX
C       M1.             NUMBER OF UNIFORM DZ INCREMENTS
C       M3              TOTAL NUMBER OF AXIAL GRID POINTS
C       N.              TOTAL NUMBER OF RADIAL GRID INCREMENTS
C       N1.             NUMBER OF UNIFORM DR INCREMENTS
C       N3              TOTAL NUMBER OF RADIAL GRID POINTS
C       NG.             NUMBER OF GROUPS OF PULSES USED FOR NON-CODED PULSE
C                       CALCULATIONS
C       NGX.            INDEX INDICATING WHETHER OR NOT MULTIPLE PULSES ARE
C                       TREATED INDIVIDUALLY(NGX=0), OR IN GROUPS(NGX=1)
C       NP              NUMBER OF TIME STEPS DURING PULSE
C       NPG(L).         NUMBER OF PULSES IN SUCCESSIVE GROUPS
C       NPR(L)          NUMBER OF PULSES REPRESENTED BY PARTICULAR PULSE,
C                       SET =0 EXCEPT FOR LAST OF A SERIES OF INDIVIDUAL PULSES
C       NPULSE.         NUMBER OF LASER PULSES CONSIDERED
C       NTP.            MINIMUM NUMBER OF TIME STEPS USED TO EMBRACE PULSE
C                       WIDTH ASSOCIATED WITH SINGLE PULSE EXPOSURES
C       NTX.            NUMBER OF TIME STEPS DESIRED FOLLOWING EXPOSURE,
C                       SHOULD BE SET EQUAL TO TO RELATIVELY LARGE NUMBER TO
C                       ENSURE ALL DAMAGE HAS OCCURRED. CODE WILL END COMP-
C                       UTATIONS IF DAMAGE HAS CEASED. NTX VALUES OF ABOUT 20
C                       SHOULD SUFFICE.  ALSO USED TO CHECK IF SUFFICIENT TIME
C                       STEPS HAVE BEEN ALLOCATED IN ARRAYS INVOLVING K, SO
C                       DO NOT USE EXTREMELY LARGE NUMBERS OF ORDER OF MK
C       NW.             NUMBER OF TIMES TEMPERATURE CALCULATIONS ARE RECYCLED
C                       IN ESTIMATING RATES OF HEAT LOSS DUE TO STEAM GENERATION
C       POW             LASER POWER,WATTS
C       POWER(K)        LASER POWER AT K-TH TIME STEP,WATTS
C       POWRC(L).       LASER POWERS OF SUCCESSIVE CODED PULSES,WATTS
C       POWN.           LASER POWER OF NON-CODED PULSES (ALL EQUAL),WATTS
C       PX(L).          MAGNITUDE OF IRREGULAR LASER PROFILE AT RADIAL
C                       DISTANCES RX(L), VALUES NEED ONLY TO BE RELATIVE, DIMEN-
C                       SIONLESS
C       P0              PREVIOUS LASER POWER POW,WATTS
C       P1              MOST RECENT LASER POWER POW,WATTS
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C       QP              FACTOR ADJUSTING MAGNITUDE OF PROFILE FOR POWER OF
C                       1 WATT, CAL/CM2-SEC-WATT
C       R(J)            RADIAL DISTANCES STARTING AT R(1)=0. AND ENDING AT
C                       R(N3)=RN,CM
C       RB              PEAK TEMPERATURE IN C AT DEPTHS AT WHICH STEAM CANNOT
C                       ESCAPE
C       REF.            REFLECTIVITY OF SURFACE OF SKIN FOR RADIATION OF GIVEN
C                       WAVELENGTH,DIMENSIONLESS
C       REPET.          REPETITION RATE FOR NON-CODED PULSES,PULSES/SEC
C       RGV             MAXIMUM TEMPERATURE FOR 2 OR 3-D PLOTS,C
C       RIM.            RADIUS AT WHICH NORMALIZED GAUSSIAN INTENSITY EQUALS
C                       CUT, CM
C       RINT            INCREMENTALLY SMALL RADIAL DISTANCE USED TO INTEGRATE
C                       IRREGULAR PROFILES, CM
C       RN              MAXIMUM RADIAL DISTANCE,CM
C       RUNIF.          RADIAL EXTENT OF UNIFORM PROFILE,CM
C       RX(L).          RADIAL DISTANCES AT WHICH INTENSITIES PX(L) ARE SPEC-
C                       IFIED,CM
C       R1,R2,R3        FACTORS BY WHICH AXIAL INCREMENTS,RADIAL INCREMENTS,AND
C                       TIME STEPS ARE EXPANDED,DIMENSIONLESS
C       S(I,J)          RATE OF HEAT DEPOSITION PER UNIT VOLUME OF TISSUE AT
C                       Z(I),R(J),CAL/CM3-SEC-WATT
C       SHF.            DIAMETER OF HAIR FOLLICLE,CM
C       SHO.            SPECIFIC HEAT OF NON-WATER CONSTITUENTS IN SWEAT,
C                       CAL/GM-C
C       SH1.,SH2.       CONSTANTS FOR CALCULATING SPECIFIC HEAT OF TISSUES
C                       AS FUNCTION OF WATER CONTENT,CAL/GM-C
C       SS(I)           GRAMS OF NON-WATER CONSTITUENTS PER CM3 AT Z(I)
C       SW(I,J)         ESTIMATED FLUX EXPENDED IN EVAPORATING WATER,CAL/CM3-SEC
C       TB(L).          THICKNESSES OF SUCCESSIVE LAYERS USED TO DESCRIBE BLOOD
C                       FLOW BL(L),CM
C       TBL(L).         TEMPERATURE IN C AT WHICH PRESSURE EQUALS L ATMOSPHERES
C       TDERM.          THICKNESS OF DERMIS,CM
C       TE.             ENVIRONMENTAL TEMPERATURE,C
C       TEPID.          THICKNESS OF EPIDERMIS,CM
C       TH(L).          THICKNESSES OF SUCCESSIVE SKIN LAYERS USED TO DESCRIBE
C                       ABS(L),CM
C       TTIME           TOTAL ELAPSED TIME,SEC
C       TIME1(KK).,     TIMES BETWEEN WHICH TEMPERATURES WILL BE PRINTED,SEC
C       TIME2(KK).
C       TO.             INITIAL SKIN TEMPERATURE,C
C       TOE             INITIAL TEMPERATURE OF SKIN ABOVE THAT OF ENVIRONMENT,C
C       TSWEAT.         THICKNESS OF SWEAT LAYER,CM
C       V,VO            NEW AND PREVIOUS TEMPERATURES ABOVE ENVIRONMENTAL
C                       TEMPERATURE TE,C
C       VHF             PEAK TEMPERATURE OF HAIR FOLLICLE,C
C       VSH(I,J)        VOLUMETRIC HEAT CAPACITY OF SKIN AT Z(I),R(J),CAL/CM3-C
C       WAVEL.          WAVELENGTH OF LASERS RADIATION,MICRONS
C       WW(I)           GRAMS OF WATER PER CM3 AT DEPTH Z(I)
C       WO.,W1.,W2.,    GRAMS OF WATER PER CM3 OF SWEAT,JUST BELOW EPIDERMAL
C       W3.             SURFACE,DERMIS, AND SUBCUTANEOUS TISSUES, RESPECTIVELY
C       XC.             FACTOR BY WHICH TIME STEPS ARE PROGRESSIVELY INCREASED.
C                       IF TEMPERATURES COMMENCE TO OSCILLATE JUST PRIOR TO
C                       PULSES, REDUCE XC CLOSER TO 1
C       XP(L)           NUMBER OF PULSES REPRESENTED BY PARTICULAR PULSE IN
C                       DAMAGE CALCULATIONS, ALWAYS 1 EXCEPT WHEN PULSES ARE
C                       GROUPED TO CONSERVE COMPUTATIONAL TIME
C       X1,X2,X3...     DUMMY PARAMETERS
C       ZBL             DEPTH AT WHICH TISSUES MAY SEPARATE TO FORM BLISTER,CM
C                       ,MUST BE EQUAL OR GREATER THAN DEPTH ZDEP
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C      ZDEP           DEPTH BENEATH WHICH WATER DOES NOT ESCAPE,CM
C      ZE(L)          DEPTH EQUAL TO TH(1)+TH(2)...TH(L-1) FOR L GREATER
C                     THAN 1,OTHERWISE=0 ,CM
C      ZH(I)          DEPTHS BELOW SKIN SURFACE, EQUALS (Z(I)+Z(I+1))/2,
C                     CM
C      ZM             MAXIMUM AXIAL DISTANCE,CM
C      ZR,            CONSTANT CONTROLLING SIZE OF MINIMUM TIME STEP DTO,
C                     SHOULD BE 0.5 OR SLIGHTLY GREATER,TEMPERATURES WILL
C                     OSCILLATE IF ZR IS TOO LARGE, DIMENSIONLESS
C      ZZ,            FACTOR BY WHICH SMALLEST TIME STEP IS PROGRESSIVELY
C                     INCREASED IN TREATING SUCEEDING PULSES, USED TO CON-
C                     SERVE COMPUTATIONAL TIME WHEN GREATER THAN 1, IF TEMP-
C                     ERATURES COMMENCE TO OSCILLATE AFTER SEVERAL PULSES
C                     REDUCE ZZ CLOSER TO 1(NEVER LOWER), DIMENSIONLESS
C      ZW(L),         NUMBERS USED TO ESTIMATE HEAT LOSSES DUE TO STEAM
C                     GENERATION, DIMENSIONLESS
C *** DIMENSIONING OF ARRAYS
C      -------------------
C      ARRAYS WITH DIMENSION KT,---DTX,POWER,  AND XP
C      ARRAYS WITH DIMENSION KX,---TIME1,AND TIME2
C      ARRAYS WITH DIMENSION LB,---BL,AND TB
C      ARRAYS WITH DIMENSION LR,---PX,AND RX
C      ARRAYS WITH DIMENSION LZ,---ABS,IZ,TH,AND ZE
C      ARRAYS WITH DIMENSION M3,---CH,CXC,CXR,DXC,DXR,FXC,FXR,JM,Z,ZH,WW,
C      XR1,XR2,XR3,XR4,XR5,XZ1,XZ2,XZ3,XZ4,AND XZ5
C      ARRAYS WITH DIMENSIONS M3,N3,---A1,A2,A3,B1,B2,B3,CON,DD,S,SS,SW,
C      V,VSH,VXO,VXX,AND WATER
C      ARRAYS WITH DIMENSION NG,---NPG,AND NPR
C      ARRAYS WITH DIMENSION NPULSE,--DPULSC,AND POWERC
C      ARRAY WITH DIMENSION NW,---ZW
C      ARRAYS WITH DIMENSION N3,---HR,AND R
C
C *** INFORMATION FOR INPUTING DATA INTO CODE
C      ----------------------------------
C      N1 GREATER THAN OR EQUAL TO 2 , NK LESS THAN TIME INTERVAL DIMENSION
C      KIM, RUNIF, AND RX(LR) GREATER THAN SHF
C      ZBL GREATER THAN OR EQUAL TO ZDEP
C      ALL DEPTH INPUT DATA REFERRED TO SKIN SURFACE---NOT FROM SURFACE
C      OF ANY SWEAT LAYER. THIS INCLUDES DEPID,DHF,TB(L),TEPID,TH(L),
C     ZBL, AND ZDEP
C      IF TEMPERATURE OSCILLATIONS ARE EXPERIENCED EXAMINE WHEN THEY OCCUR.
C      IF IMMEDIATELY FOLLOWING THE START OR END OF THE FIRST FEW PULSES,
C      REDUCE ZR, IF BETWEEN THE FIRST TWO PULSES REDUCE XC, IF AFTER SEVERAL
C      PULSES REDUCE ZZ.
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C *** IRREGULAR PROFILE
   18 READ(5,11)LR,N1,N                                            12,IRREG
      READ(5,3)(RX(L),L=1,LR)                                      12,IRREG
      READ(5,3)(PX(L),L=1,LR)                                      12,IRREG
      X0=RX(LR)
      DR=X0/N1
   21 READ(5,22)WAVEL,XC,ZR,ZZ,LASER,NPULSE,NGX,NTX                13
   22 FORMAT(4F7.1,4I7)
      IF(LASER.EQ.2)GO TO 30
C *** NON-CODED LASER PULSES
      IF(NPULSE.GT.1)GO TO 24
      READ(5,2)NTP,DPULSE,POWX                                     14,NC,1
      XX=DPULSE
      GO TO 40
   24 READ(5,2)NTP,REPET,DPULSE,POWX                               14,NC,X
      XX=(NPULSE-1)/REPET+DPULSE
      IF(NGX.EQ.1)GO TO 26
      DO 25 L=1,NPULSE
      NPG(L)=1
   25 NPR(L)=1
      NG=NPULSE
      GO TO 40
   26 READ(5,11)NG                                                 14,NC,SP
      READ(5,11)(NPG(L),L=1,NG)                                    14,NC,SP
      READ(5,11)(NPR(L),L=1,NG)                                    14,NC,SP
      GO TO 40
C *** CODED PULSES
   30 READ(5,11)NTP                                                14,CODED
      READ(5,3)(DPULSC(L),L=1,NPULSE)                              14,CODED
      READ(5,3)(POWERC(L),L=1,NPULSE)                              14,CODED
C *** DETERMINE DZ,ZM AND RN
   40 X2=0.
      X4=0.
      L=1
   41 X2=X2+ABS(L)*TH(L)
      X4=X4+TH(L)
      L=L+1
      IF(X2.LT.8..AND.L.LE.LZ)GO TO 41
      READ(5,11)M                                                  15
      IF(LASER.EQ.1)GO TO 44
      XX=0.
      DO 42 L=1,NPULSE
   42 XX=XX+DPULSC(L)
   44 ALPHA=(CON1+CON2*W1/D1)/(SH1*D1+SH2*W1)
      X3=2.*SQRT(ALPHA*XX)
      N3=N+1
      M3=M+1
      ZM=3.0*(X4+X3)
      M1=1
      DZ=(TSWEAT+TEPID)/M1
      IF(DHF.GT.ZM)GO TO 46
      IF(IPROF.EQ.0)DR=(RUNIF-SHF/2.)/(N1-1.5)
      IF(IPROF.EQ.1)DR=(RIM-SHF/2.)/(N1-1)
      IF(IPROF.EQ.2)DR=(RX(LR)-SHF/2.)/(N1-1)
   46 RN=1.5*(X0+X3)
      READ(5,11)ID1,ID2,JD1,JD2,ITYPE,KTYPE,KX                     16
      ITYPEX=ITYPE
      READ(5,3)(TIME1(L),L=1,KX)                                   17
      READ(5,3)(TIME2(L),L=1,KX)                                   18
      READ(5,2)NW,(ZW(L),L=1,NW)                                   19
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      WRITE(6,48)(ZW(L),L=1,NW)                                         ***
   48 FORMAT(1H ,3HZW=,10F6.2)
      READ(5,3)DB1,DB2,DB3,DB5                                          20
      WRITE(6,49)DB1,DB2,DB3,DB5                                        ***
   49 FORMAT(1H0,4HDB1=,4E10.4)
      CALL TIME                                                         CALL 1
      CALL GRID                                                         CALL 1
      CALL PROF                                                         CALL 1
      IF(KTYPE.EQ.0)GO TO 55
C *** DATA/CARDS FOR 2 OR 3-D PLOTS
      READ(5,11)II1,II2,II3,JJ1,JJ2                                     21
      WRITE(1,50)II1,II2,II3,JJ1,JJ2                                    ***
   50 FORMAT(5I7)
      WRITE(1,50)N3,M3                                                  ***
      WRITE(1,52)(R(J),J=1,N3)                                          ***
      WRITE(1,52)(Z(I),I=1,M3)                                          ***
   52 FORMAT(10F7.4)
   55 WRITE(6,58)ABSC,ABSW,CB,CON1,CON2,D0,D1,D2,D3,DEPID,HAIR,REF,SH0,
     1SH1,SH2,TDERM,TE,TEPID,TO,TSWEAT,W0,W1,W2,W3,WAVEL,XC,ZDEP,ZR,ZZ
   58 FORMAT(1H ,5HABSC=,F7.0,2X,5HABSW=,F7.0,2X,3HCB=,F7.3,2X,5HCON1=,
     1F8.5,2X,5HCON2=,F8.5/1X,3HD0=,F6.3,2X,3HD1=,F6.3,2X,3HD2=,F6.3,
     22X,3HD3=,F6.3,2X,6HDEPID=,F7.4/1X,5HHAIR=,F7.2,2X,4HREF=,F7.2,2X,
     34HSH0=,F7.4,2X,4HSH1=,F7.4,2X,4HSH2=,F7.4/1X,6HTDERM=,F7.4,2X,
     43HTE=,F5.0,2X,6HTEPID=,F7.4,2X,3HTO=,F5.0,2X,7HTSWEAT=,F7.4/1X,
     53HW0=,F6.3,2X,3HW1=,F6.3,2X,3HW2=,F6.3,2X,3HW3=,F6.3,2X,6HWAVEL=,
     6F6.3/1X,3HXC=,F6.3,2X,5HZDEP=,F6.3,2X,3HZR=,F5.1,2X,3HZZ=,F7.2)
      WRITE(6,59)IPROF,LASER,LS,LZ,N,N1,M,M1,NPULSE,NGX,NTX             ***
   59 FORMAT(1H ,6HIPROF=,I1,2X,6HLASER=,I1,2X,3HLS=,I2,2X,3HLZ=,I2,2X,
     12HN=,I2,2X,3HN1=,I2,2X,2HM=,I2,2X,3HM1=,I2/1X,7HNPULSE=,I4,2X,4HNG
     2X=,I1,2X,4HNTX=,I2)
      WRITE(6,60)ZBL,HW,DTEMP,DHF,SHF                                   ***
   60 FORMAT(1H ,4HZBL=,E8.3,2X,3HHW=,E8.3,2X,6HDTEMP=,F6.0,2X,4HDHF=,
     1E8.3/1X,4HSHF=,E8.3)
      IF(IPROF.EQ.0)WRITE(6,64)RUNIF                                    ***
   64 FORMAT(1H ,6HRUNIF=,E9.3)
      IF(IPROF.EQ.1)WRITE(6,65)CUT,RIM                                  ***
   65 FORMAT(1H ,4HCUT=,F8.4,2X,4HRIM=,F8.4)
      IF(IPROF.EQ.2)WRITE(6,66)LR,(RX(L),L=1,LR)                        ***
   66 FORMAT(1H ,3HLR=,I3,3HRX=/(1X,10E8.3))
      IF(IPROF.EQ.2)WRITE(6,67)(PX(L),L=1,LR)                           ***
   67 FORMAT(1H ,3HPX=/(1X,10E8.3))
      IF(LASER.EQ.2)GO TO 72
      WRITE(6,68)DPULSE,NTP,POWX                                        ***
   68 FORMAT(1H ,7HDPULSE=,E9.3,2X,4HNTP=,I2,2X,5HPOWX=,E9.3)
      IF(NPULSE.GT.1)WRITE(6,69)(NPG(L),L=1,NG)                         ***
   69 FORMAT(1H ,4HNPG=/(1X,10I7))
      IF(NPULSE.GT.1)WRITE(6,70)(NPR(L),L=1,NG)                         ***
   70 FORMAT(1H ,4HNPR=/(1X,10I7))
      IF(NPULSE.GT.1)WRITE(6,71)REPET                                   ***
   71 FORMAT(1H ,6HREPET=,E9.4)
      GO TO 78
   72 WRITE(6,74)(DPULSC(L),L=1,NPULSE)                                 ***
   74 FORMAT(1H ,7HDPULSC=,/(1X,10E8.3))
      WRITE(6,75)(POWERC(L),L=1,NPULSE)                                 ***
   75 FORMAT(1H ,7HPOWERC=/(1X,10E8.3))
   78 WRITE(6,79)ID1,ID2,ITYPE,JD1,JD2,KTYPE                            ***
   79 FORMAT(1H ,4HID1=,I2,2X,4HID2=,I2,2X,6HITYPE=,I2,2X,4HJD1=,I2,2X,
     14HJD2=,I2,2X,6HKTYPE=,I1)
      WRITE(6,80)(TIME1(L),L=1,KX),(TIME2(L),L=1,KX)                    ***
   80 FORMAT(1H ,8HTIME1-2=/(1X,10E8.3))
```

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      WRITE(6,81)(TH(L),L=1,LZ)                                        ***
   81 FORMAT(1H ,3HTH=/(1X,10F7.4))
      WRITE(6,82)(ABS(L),L=1,LZ)                                       ***
   82 FORMAT(1H ,4HABS=/(1X,10F7.0))
      WRITE(6,83)(TB(L),L=1,LB)                                        ***
   83 FORMAT(1H ,3HTB=/(1X,10F7.4))
      WRITE(6,84)(BL(L),L=1,LB)                                        ***
   84 FORMAT(1H ,3HBL=/(1X,10F7.4))
      WRITE(6,85)DAM(1,1),DAM(1,2),DAM(2,1),DAM(2,2)                   ***
   85 FORMAT(1H ,9HDAM(1,1)=,F6.1,2X,9HDAM(1,2)=,F6.0,2X,9HDAM(2,1)=,
     1F6.1,2X,9HDAM(2,2)=,F6.0)
      WRITE(6,86)DR,RN,DZ,ZM,NG                                        ***
   86 FORMAT(1H ,3HDR=,F6.4,2X,3HRN=,F8.4,2X,3HDZ=,F6.4,2X,3HZM=,F8.4,
     12X,3HNG=,I2)
      TTIME=0.
      IMAX=M
      JMAX=N
      LMI=M
      X1=TSWEAT+DEPID
      X2=TSWEAT+ZDEP
      ..S=0.
      RQV=TOE
      IB=1
      RB=TOE
      DO 88 I=1,M3
      IF(X1.GT.Z(I))II=I+1
      IF(X2.GE.Z(I))IP=I+1
      DO 88 J=1,N3
      D(I,J)=1.E-10
      V(I,J)=TOE
   88 VO(I,J)=TOE
C     START OF TEMPERATURE AND DAMAGE CALCULATIONS
C     ----------------------------------------
      KK=1
      K=1
   90 DT=DTX(K)
      TTIME=TTIME+DT
      POW=POWER(K)
      IF(IMAX.GT.0)CALL CWATER                                         CALL X
      IF(IMAX.GT.0)CALL BA                                             CALL X
      IF(LMI.GE.II)CALL HTDEP                                          CALL X
      IF(K.GT.1)GO TO 105
      WRITE(6,100)                                                     ***
  100 FORMAT(1H ,22HHEAT DEPOSITION RATES=,10H----------)
      WRITE(6,101)(R(J),J=JD1,JD2)                                     ***
  101 FORMAT(1H ,10X,2HR=,9F8.4/13X,30H------------------------------)
      DO 104 I=ID1,ID2
      WRITE(6,102)Z(I),(S(I,J),J=JD1,JD2)                              ***
  102 FORMAT(1H ,2HZ=,F8.4,2X,9E8.3)
  104 CONTINUE
  105 WRITE(6,106)DT,TTIME,POW,XP(K),IMAX,JMAX                         ***
  106 FORMAT(1H0,3HDT=,E8.3,2X,5HTIME=,E9.4,2X,6HPOWER=,E9.3,2X,3HXP=,
     1F5.0,7H  IMAX=,I2,7H  JMAX=,I2)
      CALL TEMP                                                        CALL
      CALL DAMAGE                                                      CALL
      IF(XP(K).LT..99)GO TO 119
      IF(ITYPEX.LT.ITYPE.OR.KK.GT.KX)GO TO 119
      IF(TTIME.LT.TIME1(KK).OR.TTIME.GT.TIME2(KK))GO TO 119
      DO 107 I=ID1,ID2
      DO 107 J=JD1,JD2
```

```
107 VT(I,J)=V(I,J)-TOE
    WRITE(6,101)(R(J),J=JD1,JD2)
    DO 110 I=ID1,ID2
    WRITE(6,108)Z(I),(VT(I,J),J=JD1,JD2)
108 FORMAT(1H ,2HZ=,F8.4,2X,9F8.1)
110 CONTINUE
    ITYPEX=0
    IF(KTYPE.EQ.0)GO TO 118
    DO 112 I=II1,II2
    DO 112 J=JJ1,JJ2
112 VT(I,J)=V(I,J)-TOE
    DO 116 I=II1,II2
    WRITE(1,115)(VT(I,J),J=JJ1,JJ2)
115 FORMAT(10F7.1)
116 CONTINUE
    WRITE(1,52)RGV
118 ITYPEX=ITYPEX+1
119 IF(TTIME.GT.TIME2(KK).AND.KK.LT.KX)KK=KK+1
    IF(V(1,1).GT.ZB5)ZB5=V(1,1)
    K=K+1
    IF(K.LE.KT)GO TO 90
    WRITE(6,122)
122 FORMAT(1H ,7HDAMAGE=,10H----------)
    WRITE(6,101)(R(J),J=JD1,JD2)
    DO 124 I=II,ID2
    WRITE(6,123)Z(I),(D(I,J),J=JD1,JD2)
123 FORMAT(1H ,2HZ=,F8.4,2X,9E8.2)
124 CONTINUE
    X4=1.
    RB=RB+TE
    IF(RB.LT.100.)GO TO 130
    L=2
126 IF(RB.LT.TBL(L))GO TO 128
    L=L+1
    IF(L.LE.27)GO TO 126
128 X1=(RB-TBL(L-1))/(TBL(L)-TBL(L-1))
    X4=L-1.+X1
130 WRITE(6,132)X4,Z(IB)
132 FORMAT(1H ,14HPEAK PRESSURE=,F7.1,5H ATM.,3X,6HDEPTH=,F8.4,3H CM)
    VHF=VHF+TE
    IF(IB.EQ.IHF)WRITE(6,133)VHF
133 FORMAT(1H ,37HLOCATED AT HAIR FOLLICLE(TEMPERATURE=,F5.0,3H C))
    JDR=0
    DO 140 J=1,N
    IF(D(II,J).GE.1.)JDR=J
140 CONTINUE
    IF(JDR.EQ.0)GO TO 160
    X1=ALOG(D(II,JDR)/D(II,JDR+1))/(R(JDR+1)-R(JDR))
    X2=R(JDR)+ALOG(D(II,JDR))/X1
    WRITE(6,144)X2
144 FORMAT(1H0,17HRADIUS OF DAMAGE=, F7.4,3H CM)
    DO 150 I=II,M
    IF(D(I,1).GE.1.)IDZ=I
150 CONTINUE
    X1=ALOG(D(IDZ,1)/D(IDZ+1,1))/(Z(IDZ+1)-Z(IDZ))
    X2=Z(IDZ)+ALOG(D(IDZ,1))/X1
    WRITE(6,154)X2
154 FORMAT(1H0,16HDEPTH OF DAMAGE=, F7.4,3H CM)
160 LDB=0
    IF(D(II,1).GT.DB1)LDB=1
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      IF(D(II,1).GT.DB2)LDB=2
      IF(D(II,1).GT.DB3)LDB=3
      IF(JW.GT.1)LDB=4
      IF(ZB5+TE.GT.DB5)LDB=5
      WRITE(6,162)LDB
  162 FORMAT(1H0,15HDEGREE OF BURN=,I1)
      STOP
      END
```

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```
      -------------SUBROUTINE TIME-------------
C *** TIME COMPUTES LASER POWERS POWER(K) FOR EACH TIME STEP DTX(K)
      COMMON ABS(11),ABSC,ALPHA,A1(35,35),A2(35,35),A3(35,35),B1(35,35),
     1B2(35,35),B3(35,35),BL(11),BLOOD(35),CB,CON1,CON2,CON(35,35),CUT,
     2D(35,35),DAM(2,2),DHF,DR,DT,DTX(200),DPULSE,DPULSC(50),DTEMP,DZ,
     3D0,D1,D2,D3,H,HAIR,HR(35),HW,IB,IHF,II,IMAX,IP,IPROF,IW,JMAX,K,KT,
     4LASER,LB,LMI,LNJ,LR,LZ,M,MK,M1,M3,N,N1,N3,NG,NGX,NPG(30),NPR(30),
     5NPULSE,NTP,NTX,NW,POW,POWER(200),POWERC(50),POWX,PX(50),R(35),RB,
     6REF,REPET,RIM,RGV,RW,RUNIF,RX(50),S(35,35),SHF,SH0,SH1,SH2,TB(11),
     7TDERM,TE,TEPID,TH(11),TOE,TSWEAT,TTIME,V(35,35),VHF,VO(35,35),
     8VSH(35,35),WATER(35,35),W0,W1,W2,W3,XC,XP(200),Z(35),ZBL,ZDEP,
     9ZM,ZR,ZW(10),ZZ,DBS,JW
      DO 2 K=1,MK
      POWER(K)=0.
    2 XP(K)=1.
      X0=SHF
      IF(ZM.LT.DHF)X0=1.E+10
      X1=AMIN1(DR,DZ,X0)
      DTO=ZR*X1*X1/ALPHA
      DTT=DTO
      XX5=XC-1.
      XX6=ALOG(XC)
      IF(LASER.EQ.2)GO TO 70
C *** NON-CODED PULSES-------------------------------------------------
      IF(NPULSE.GT.1)GO TO 31
C *** EXPOSURES INVOLVING A SINGLE PULSE
      DT1=DPULSE/NTP
      IF(DT1.GT.DTO)GO TO 8
      DO 4 K=1,NTP
      DTX(K)=DT1
    4 POWER(K)=POWX
      L3=NTP
      GO TO 29
    8 L1=ALOG(DT1/DTO)/XX6+1
      X1=DTO*(XC**L1-1.)/XX5
      IF(X1.GE.DPULSE)GO TO 20
      L2=(DPULSE-X1)/DT1+1
      DT1=(DPULSE-X1)/L2
      DO 10 K=1,L1
      DTX(K)=DTT
      POWER(K)=POWX
   10 DTT=XC*DTT
      L2=L1+L2
      L1=L1+1
      DO 12 K=L1,L2
      DTX(K)=DT1
   12 POWER(K)=POWX
      L3=L2
      GO TO 29
   20 X1=2.
   22 R3=EXP(ALOG((DPULSE*X1-DPULSE)/DTO+1.)/L1)
      IF(R3/X1.GT..99999.AND.R3/X1.LT.1.00001)GO TO 24
      X1=R3
      GO TO 22
   24 WRITE(6,26)R3
   26 FORMAT(1H ,3HR3=,F8.4)
      DO 28 K=1,L1
      DTX(K)=DTT
      POWER(K)=POWX
   28 DTT=R3*DTT
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```
      L3=L1
   29 L1=L3+1
      L2=L3+NTX
      DO 30 K=L1,L2
      DTX(K)=DTO
   30 DTO=XC*DTO
      KT=L2
      GO TO 120
C *** EXPOSURES INVOLVING MULTIPLE PULSES
   31 DTO=DTO/ZZ
      XX2=1./REPET-DPULSE
      XX3=POWX*DPULSE*REPET
      XX4=XX2/(XC+1.)
      K=0
      DO 50 L=1,NG
      DTO=ZZ*DTO
      IF(NPG(L).GT.1)GO TO 40
C  *  SINGLE PULSES
      NP=DPULSE/DTO
      IF(NP.LT.2)NP=2
      XX1=DPULSE/NP
      L2=K+1
      L3=K+NP
      DO 32 K=L2,L3
      DTX(K)=XX1
      POWER(K)=POWX
   32 XP(K)=NPR(L)
      K=L3
      IF(XX4.GT.DTO)GO TO 36
      K=K+1
      DTX(K)=XX4
      XP(K)=NPR(L)
      K=K+1
      DTX(K)=XX2-XX4
      XP(K)=NPR(L)
      GO TO 50
   36 L1=ALOG(XX2*XX5/DTO+1.)/XX6+1.
      DT2=XX4*XX5/(XC**L1-1.)
      L2=K+1
      L3=K+L1
      DO 38 K=L2,L3
      DTX(K)=DT2
      XP(K)=NPR(L)
   38 DT2=XC*DT2
      K=L3
      GO TO 50
C  *  GROUPS OF SEVERAL PULSES
   40 X2=NPG(L)/REPET
      IF(X2.GT.DTO)GO TO 46
      K=K+1
      DTX(K)=X2
      POWER(K)=XX3
      XP(K)=0.
      GO TO 50
   46 L1=ALOG(X2*XX5/DTO+1.)/XX6+1.
      DT2=X2*XX5/(XC**L1-1.)
      L2=K+1
      L3=K+L1
```

```
      DO 48 K=L2,L3
      DTX(K)=DT2
      POWER(K)=XX3
      XP(K)=0.
   48 DT2=XC*DT2
      K=L3
   50 CONTINUE
      L2=K+1
      L3=K+NTX
      DO 54 K=L2,L3
      DTX(K)=DTO
   54 DTO=XC*DTO
      KT=L3
      GO TO 120
C *** CODED PULSES-----------------------------------------------------
   70 K=0
      DTO=DTO/ZZ
      DO 100 L=1,NPULSE
      DTO=ZZ*DTO
      DTT=DTO
      DT1=DPULSC(L)/NTP
      IF(DT1.GT.DTO)GO TO 76
      L1=K+1
      L2=K+NTP
      DO 74 K=L1,L2
      DTX(K)=DT1
   74 POWER(K)=POWERC(L)
      K=L2
      GO TO 100
   76 L1=ALOG(DT1/DTO)/XX6+1
      X1=DTO*(XC**L1-1.)/XX5
      IF(X1.GE.DPULSC(L))GO TO 90
      L2=(DPULSC(L)-X1)/DT1+1
      DT1=(DPULSC(L)-X1)/L2
      L3=K+1
      L4=K+L1
      DO 80 K=L3,L4
      DTX(K)=DTT
      POWER(K)=POWERC(L)
   80 DTT=XC*DTT
      L5=L4+1
      L6=L4+L2
      DO 82 K=L5,L6
      DTX(K)=DT1
   82 POWER(K)=POWERC(L)
      K=L6
      GO TO 100
   90 X1=2.
   92 R3=EXP(ALOG((DPULSC(L)*X1-DPULSC(L))/DTO+1.)/L1)
      IF(R3/X1.GT..99999.AND.R3/X1.LT.1.00001)GO TO 94
      X1=R3
      GO TO 92
   94 WRITE(6,26)R3
      L2=K+1
      L3=K+L1
      DO 98 K=L2,L3
      DTX(K)=DTT
      POWER(K)=POWERC(L)
   98 DTT=R3*DTT
      K=L3
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```
100 CONTINUE
    L3=K+1
    L4=K+NTX
    DO 110 K=L3,L4
    DTX(K)=DTO
110 DTO=XC*DTO
    KT=L4
120 IF(KT.GT.MK)WRITE(6,121)KT
121 FORMAT(1H ,36HNUMBER OF TIME STEPS EXCEEDS DIMENSION MK, KT=,I3)
    IF(KT.GT.MK)STOP
    WRITE(6,122)(DTX(K),K=1,KT)
122 FORMAT(1H ,4HDTX=/(1X,8E9.3))
    WRITE(6,124)(POWER(K),K=1,KT)
124 FORMAT(1H ,6HPOWER=/(1X,8E9.3))
    WRITE(6,126)(XP(K),K=1,KT)
126 FORMAT(1H ,3HXP=/(1X,8F9.0))
    RETURN
    END
```

```
C *** GRID COMPUTES THE RADIAL AND AXIAL SPACE STEPS R(J) AND Z(I)
      COMMON ABS(11),ABBC,ALPHA,A1(35,35),A2(35,35),A3(35,35),B1(35,35),
     1B2(35,35),B3(35,35),BL(11),BLOOD(35),CB,CON1,CON2,CON(35,35),CUT,
     2D(35,35),DAM(2,2),DHF,DR,DT,DTX(200),DPULSE,DPULSC(50),DTEMP,DZ,
     3DD,D1,D2,D3,H,HAIR,HR(35),HN,IB,IHF,II,IMAX,IP,IPROF,IW,JMAX,K,KT,
     4LASER,LA,LMI,LNJ,LR,LZ,M,MK,M1,M3,N,N1,N3,NB,NGX,NPR(30),NPR(30),
     5NPULSE,NTP,NTX,NW,POW,POWER(200),POWERC(50),POWX,PX(50),R(35),RR,
     6REF,REPET,RIM,RBV,RN,RUNIF,RX(50),S(35,35),BHF,BH0,BH1,BH2,TB(11),
     7TDERM,TE,TEPID,TH(11),TOE,TSWEAT,TTIME,V(35,35),VHF,VO(35,35),
     8VBH(35,35),WATER(35,35),W0,W1,W2,W3,XC,XP(200),Z(35),ZBL,ZDEP,
     9ZM,ZR,ZW(10),ZZ,DBS,JW
      M4=M1+1
      N4=N1+1
C *** CALCULATE BTETCH CONSTANT R2
      CK=N3-N1
      CP=RN-(N1-1)*DR
      IF(DHF.LT.ZM)CP=RN-(N1-2)*DR+BHF/2.
      X1=2.
   10 R2=EXP(ALOG((CP*X1-CP)/DR+1.)/CK)
      IF(R2/X1.GT..999999.AND.R2/X1.LT.1.000001)GO TO 13
      X1=R2
      GO TO 10
   13 WRITE(6,14)R2
C *** CALCULATE RADIAL DISTANCES R(J)
   13 R(1)=0.
      R(2)=DR
      IF(DHF.LT.ZM)R(2)=BHF/2.
      DO 15 J=3,N4
   15 R(J)=R(J-1)+DR
      X1=R2*DR
      DO 16 J=N4,N
      R(J+1)=R(J)+X1
   16 X1=R2*X1
C *** CALCULATE AXIAL DISTANCES Z(I)
      Z(1)=0.
      DO 18 I=2,M4
   18 Z(I)=DZ*(I-1)
      DHF=DHF+TSWEAT
      TEPID=TEPID+TSWEAT
      ZBL=ZBL+TSWEAT
      ZM=ZM+TSWEAT
      IHF=0
      IF(DHF.LT.ZM)GO TO 30
C  *  HAIR FOLLICLE NOT PRESENT
      CK=M3-M1
      CP=ZM-(M1-1)*DZ
      X1=2.
   20 R1=EXP(ALOR((CP*X1-CP)/DZ+1.)/CK)
      IF(R1/X1.GT..999999.AND.R1/X1.LT.1.000001)GO TO 23
      X1=R1
      GO TO 20
   23 X1=R1*DZ
      DO 26 I=M4,M
      Z(I+1)=Z(I)+X1
   26 X1=R1*X1
      GO TO 70
C  *  HAIR FOLLICLE PRESENT
   30 LX=(M-M1)/3
      CK=LX+1
      CP=(DHF-TEPID)/2.+DZ
```

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      X1=2.
   32 R1=EXP(ALOG((CP*X1-CP)/DZ+1.)/CK)
      IF(R1/X1.GT..999999.AND.R1/X1.LT.1.000001)GO TO 34
      X1=R1
      GO TO 32
   34 X1=R1*DZ
      L1=M4+1
      L2=M4+LX
      DO 36 I=L1,L2
      Z(I)=Z(I-1)+X1
   36 X1=R1*X1
      CK=LX
      CP=(DHF-TEPID)/2.
      X1=2.
   42 R1=EXP(ALOG((CP*X1-CP)/SHF+1.)/CK)
      IF(R1/X1.GT..999999.AND.R1/X1.LT.1.000001)GO TO 44
      X1=R1
      GO TO 42
   44 L2=L2+LX
      Z(L2-1)=DHF-SHF
      Z(L2)=DHF
      Z(L2+1)=DHF+SHF
      IHF=L2
      IF(LX.LE.2)GO TO 47
      X1=R1*SHF
      L1=LX-2
      DO 46 I=1,L1
      L3=L2-1-I
      Z(L3)=Z(L3+1)-X1
   46 X1=R1*X1
   47 CK=M3-L2
      CP=ZM-DHF
      X1=2.
   52 R1=EXP(ALOG((CP*X1-CP)/SHF+1.)/CK)
      IF(R1/X1.GT..999999.AND.R1/X1.LT.1.000001)GO TO 60
      X1=R1
      GO TO 52
   60 X1=R1*SHF
      L1=L2+2
      DO 62 I=L1,M3
      Z(I)=Z(I-1)+X1
   62 X1=R1*X1
   70 X1=1000.
      DO 72 I=1,M
      X2=ZBL-Z(I)
      IF(X2*X2.GT.X1)GO TO 72
      IW=I
      X1=X2*X2
   72 CONTINUE
      WRITE(6,88)(R(J),J=1,N3)
   88 FORMAT(1H ,2HR=/(1X,8F9.4))
      WRITE(6,90)(Z(I),I=1,M3)
   90 FORMAT(1H ,2HZ=/(1X,8F9.4))
      RETURN
      END
```

```
      --------------SUBROUTINE PROF--------------
C *** PROF COMPUTES INTENSITIES OF LASER BEAM AT GIVEN RADII FOR LASER
C *** POWER OF 1 WATT---INTENSITIES IN UNITS OF CAL/CM2-SEC
      COMMON ABS(11),ABSC,ALPHA,A1(35,35),A2(35,35),A3(35,35),B1(35,35),
     1B2(35,35),B3(35,35),BL(11),BLOOD(35),CB,CON1,CON2,CON(35,35),CUT,
     2D(35,35),DAM(2,2),DMF,DR,DT,DTX(200),DPULSE,DPULSC(50),DTEMP,DZ,
     3D0,D1,D2,D3,H,HAIR,HR(35),HW,IB,IMF,II,IMAX,IP,IPROF,IW,JMAX,K,KT,
     4LASER,LB,LMI,LNJ,LR,LZ,M,MK,M1,M3,N,N1,N3,NG,NGX,NPG(30),NPR(30),
     5NPULSE,NTP,NTX,NW,POW,POWER(200),POWERC(50),POWX,PX(50),R(35),RB,
     6REF,REPET,RIM,RGV,RN,RUNIF,RX(50),S(35,35),SMF,SM0,SM1,SM2,TB(11),
     7TDERM,TE,TEPID,TH(11),TOE,TSWEAT,TTIME,V(35,35),VMF,VO(35,35),
     8VSM(35,35),WATER(35,35),W0,W1,W2,W3,XC,XP(200),Z(35),ZBL,ZDEP,
     9ZM,ZR,ZW(10),ZZ,DBS,JW
      DIMENSION FA(501),FP(501),FX(501)
      LI=500
      DO 10 J=1,N3
   10 HR(J)=0.
      DO 11 L=1,LI
   11 FX(L)=0.
      IF(IPROF.EQ.1)GO TO 44
      IF(IPROF.EQ.0)GO TO 59
C *** IRREGULAR BEAM PROFILE
      RINT=RX(LR)/(LI-1)
C  *  INTEGRATE PROFILE OVER ALL RADII TO DETERMINE QP
      X5=0.
      DO 18 L=2,LR
      X2=(PX(L)-PX(L-1))/(RX(L)-RX(L-1))
      X1=PX(L-1)-X2*RX(L-1)
      X3=X1*(RX(L)*RX(L)-RX(L-1)*RX(L-1))/2.
      X4=X2*(RX(L)*RX(L)*RX(L)-RX(L-1)*RX(L-1)*RX(L-1))/3.
   18 X5=X5+6.2832*(X3+X4)
      QP=.23906*(1.-REF)*(1.-HAIR)/X5
C  *  INTERPOLATE PROFILE AT INTERVALS OF RINT
      L2=2
      X1=0.
      DO 23 L=1,LI
   20 IF(RX(L2).GT.X1)GO TO 22
      L2=L2+1
      IF(L2.LE.LR)GO TO 20
      GO TO 23
   22 X2=(X1-RX(L2-1))/(RX(L2)-RX(L2-1))
      FX(L)=PX(L2-1)+X2*(PX(L2)-PX(L2-1))
   23 X1=X1+RINT
C     CALCULATE TOTAL AREA,FA(L), AND INTEGRAL OF FX(L) WITH RESPECT TO
C     RADIAL AREA,FP(L),FROM R=0 TO VARIOUS RADIAL DISTANCES (L-.5)*RINT
      FP(1)=3.1416*FX(1)*RINT*RINT/4.
      FA(1)=3.1416*RINT*RINT/4.
      DO 34 L=2,LI
      X1=(L-.5)*RINT
      X2=(L-1.5)*RINT
      FP(L)=FP(L-1)+FX(L)*3.1416*(X1*X1-X2*X2)
   34 FA(L)=FA(L-1)+3.1416*(X1*X1-X2*X2)
C  *  CALCULATE PROFILE HR(J) FOR ALL R(J)
      X1=0.
      X2=0.
      DO 35 J=1,N
      X3=(R(J)+R(J+1))/(2.*RINT)+.5000001
      IF(X3.LT.1.)X3=1.0000001
      L2=X3
      IF(L2.GE.LI)GO TO 35
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      X4=X3-L2
      X5=FP(L2)+X4*(FP(L2+1)-FP(L2))
      X6=FA(L2)+X4*(FA(L2+1)-FA(L2))
      HR(J)=QP*(X5-X1)/(X6-X2)
      X1=X5
      X2=X6
   35 CONTINUE
      GO TO 70
C *** GAUSSIAN BEAM PROFILE
   44 SIGMA=RIM*SQRT(-2./ALOG(CUT))
      WRITE(6,46)SIGMA
   46 FORMAT(1H0,6HSIGMA=,E8.3)
      QP=2.*.23906*(1.-REF)*(1.-HAIR)/(3.1416*SIGMA*SIGMA)
      DO 47 J=1,N
      X3=2.*R(J)*R(J)/(SIGMA*SIGMA)
      IF(X3.GT.60.)GO TO 47
      HR(J)=QP*EXP(-X3)
   47 CONTINUE
      GO TO 70
C *** UNIFORM BEAM PROFILE
   59 QP=.23906*(1.-REF)*(1.-HAIR)/(3.1416*RUNIF*RUNIF)
      DO 60 J=1,N1
   60 HR(J)=QP
   70 WRITE(6,72)(HR(J),J=1,N)
   72 FORMAT(1H ,3HHR=/(1X,8E9.3))
      RETURN
      END
```

```
      ----------------SUBROUTINE CHATER-----------
C *** CHATER COMPUTES CONDUCTIVITIES,HEAT CAPACITIES VERSUS WATER CONTENT
C *** AND BLOOD FLOWS
      COMMON ABS(11),ABSC,ALPHA,A1(35,35),A2(35,35),A3(35,35),B1(35,35),
     1B2(35,35),B3(35,35),BL(11),BLOOD(35),CB,CON1,CON2,CON(35,35),CUT,
     2D(35,35),DAM(2,2),DHF,DR,DT,DTX(200),DPULSE,DPULSC(50),DTEMP,DZ,
     3D0,D1,D2,D3,H,HAIR,HR(35),HW,IB,IHF,II,IMAX,IP,IPROF,IW,JMAX,K,KT,
     4LASER,LB,LMI,LNJ,LR,LZ,M,MK,M1,M3,N,N1,N3,NG,NGX,NPG(30),NPR(30),
     5NPULSE,NTP,NTX,NW,POW,POWER(200),POWERC(50),POWX,PX(50),R(35),RB,
     6REF,REPET,RIM,RGV,RN,RUNIF,RX(50),S(35,35),SHF,SH0,SH1,SH2,TB(11),
     7TDERM,TE,TEPID,TH(11),TOE,TSWEAT,TTIME,V(35,35),VHF,VO(35,35),
     8VSH(35,35),WATER(35,35),W0,W1,W2,W3,XC,XP(200),Z(35),ZBL,ZDEP,
     9ZM,ZR,ZW(10),ZZ,DBS,JW
      DIMENSION CH(35),DD(35),SS(35),WW(35)
      IF(K.GT.1)GO TO 40
C *** BLOOD FLOWS AT VARIOUS DEPTHS Z(I)
      DO 6 I=1,M3
    6 BLOOD(I)=0.
      L1=1
      X1=TB(1)
      I=1
    7 IF(Z(I).LT.X1)GO TO 8
      L1=L1+1
      IF(L1.GT.LB)GO TO 9
      X1=X1+TB(L1)
      GO TO 7
    8 BLOOD(I)=BL(L1)
      I=I+1
      IF(I.LE.M)GO TO 7
C *** DENSITIES DD, WATER CONTENT WW, NON-WATER CONTENT SS AND SPECIFIC
C *** HEATS CH  WITH OR WITHOUT SWEAT
    9 IF(TSWEAT.LT..0001)GO TO 20
      D1=D0
      W1=W0
   20 DO 26 I=1,M3
      IF(I.GT.1.OR.TSWEAT.GE.YEPID)GO TO 21
      DD(I)=((D1+3.*D2)*TEPID*TEPID+(6.*D1-2.*D2)*TEPID*TSWEAT+(D1-D2)*
     1TSWEAT*TSWEAT)/(4.*TEPID*(TSWEAT+TEPID))
      WW(I)=((W1+3.*W2)*TEPID*TEPID+(6.*W1-2.*W2)*TEPID*TSWEAT+(W1-W2)*
     1TSWEAT*TSWEAT)/(4.*TEPID*(TSWEAT+TEPID))
      GO TO 23
   21 IF(Z(I).GT.TSWEAT-.0001)GO TO 22
      WW(I)=W0
      DD(I)=D0
      SS(I)=D0-W0
      CH(I)=(SH0*SS(I)+W0)/D0
      GO TO 26
   22 IF(Z(I).GT.TSWEAT+TEPID)GO TO 24
      X1=(Z(I)-TSWEAT)/TEPID
      WW(I)=W1+X1*(W2-W1)
      DD(I)=D1+X1*(D2-D1)
   23 SS(I)=DD(I)-WW(I)
      CH(I)=SH1+SH2*WW(I)/DD(I)
      GO TO 26
   24 IF(Z(I).GT.TSWEAT+TEPID+TDERM)GO TO 25
      WW(I)=W2
      DD(I)=D2
      SS(I)=D2-W2
      CH(I)=SH1+SH2*W2/D2
      GO TO 26
```

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   25 WW(I)=W3
      DD(I)=D3
      SS(I)=D3-W3
      CH(I)=SH1+SH2*W3/D3
   26 CONTINUE
C *** DETERMINE INITIAL THERMAL CONDUCTIVITIES AND VOLUMETRIC HEAT CAP-
C *** ACITIES
      DO 33 I=1,N3
      WATER(I,1)=WW(I)
      VSH(I,1)=CH(I)*DD(I)
      CON(I,1)=CON1+CON2*WW(I)/DD(I)
      DO 33 J=2,N3
      WATER(I,J)=WW(I)
      CON(I,J)=CON(I,1)
   33 VSH(I,J)=VSH(I,1)
      WRITE(6,36)(CON(I,1),I=1,N3)
   36 FORMAT(1H ,4HCON=/(1X,8F9.4))                                    ---
      WRITE(6,38)(VSH(I,1),I=1,N3)
   38 FORMAT(1H ,4HVSH=/(1X,8F9.4))                                    ---
      RETURN
C *** ADJUST CONDUCTIVITIES AND HEAT CAPACITIES FOR WATER LOSS
   40 DO 44 I=1,IMAX
      DO 44 J=1,JMAX
      DDX=WATER(I,J)+SS(I)
      CHX=(SH0*SS(I)+WATER(I,J))/DDX
      IF(Z(I).GT.TSHEAT-.0001)CHX=SH1+SH2*WATER(I,J)/DDX
      VSH(I,J)=CHX*DDX
   44 CON(I,J)=CON1+CON2*WATER(I,J)/DDX
      RETURN
      END
```

```
      -------------SUBROUTINE BA---------------
C *** BA COMPUTES MATRIX ELEMENTS NEEDED FOR TEMPERATURE COMPUTATIONS
      COMMON ABS(11),ABSC,ALPHA,A1(35,35),A2(35,35),A3(35,35),B1(35,35),
     1B2(35,35),B3(35,35),BL(11),BLOOD(35),CB,CON1,CON2,CON(35,35),CUT,
     2D(35,35),DAM(2,2),DHF,DR,DT,DTX(200),DPULSE,DPULSC(50),DTEMP,DZ,
     3D0,D1,D2,D3,H,HAIR,HR(35),HW,IB,IHF,II,IMAX,IP,IPROF,IW,JMAX,K,KT,
     4LASER,LB,LMI,LNJ,LR,LZ,M,MK,M1,M3,N,N1,N3,NG,NGX,NPG(30),NPR(30),
     5NPULSE,NTP,NTX,NW,POW,POWER(200),POWERC(50),POWX,PX(50),R(35),RB,
     6REF,REPET,RIM,RGV,RN,RUNIF,RX(50),S(35,35),SHF,SH0,SH1,SH2,TB(11),
     7TDERM,TE,TEPID,TH(11),TOE,TSWEAT,TTIME,V(35,35),VHF,VO(35,35),
     8VSM(35,35),WATER(35,35),W0,W1,W2,W3,XC,XP(200),Z(35),ZBL,ZDEP,
     9ZM,ZN,ZW(10),ZZ,DBS,J=
      DIMENSION XR1(35),XR2(35),XR3(35),XR4(35),XZ1(35),XZ2(35),XZ3(35),
     1XZ4(35)
      IF(K.GT.1)GO TO 12
      DO 10 J=2,N
      X1=R(J)-R(J-1)
      X2=R(J+1)-R(J-1)
      X3=R(J+1)-R(J)
      XR1(J)=-1./(R(J)*X2)+2./(X2*X1)
      XR2(J)=-1./(X2*X2)
      XR3(J)=2./(X2*X3)+2./(X2*X1)
   10 XR4(J)=1./(R(J)*X2)+2./(X2*X3)
      DO 11 I=2,M
      X1=Z(I)-Z(I-1)
      X2=Z(I+1)-Z(I-1)
      X3=Z(I+1)-Z(I)
      XZ1(I)=2./(X2*X1)
      XZ2(I)=-1./(X2*X2)
      XZ3(I)=2./(X2*X3)+2./(X2*X1)
   11 XZ4(I)=2./(X2*X3)
   12 L1=IMAX+1
      L2=JMAX+1
      DO 23 J=1,L2
      IF(J.LT.JW.AND.IW.EQ.2)GO TO 19
      A1(1,J)=0.
      A2(1,J)=(CON(1,J)+CON(2,J))/(DZ*DZ)+H/DZ+BLOOD(1)*CB/2.
      A3(1,J)=(CON(1,J)+CON(2,J))/(DZ*DZ)
   19 DO 23 I=2,L1
      IF(J.LT.JW.AND.IW.EQ.IW-1)GO TO 23
      IF(J.LT.JW.AND.IW.EQ.IW)GO TO 23
      A1(I,J)=CON(I,J)*XZ1(I)+(CON(I+1,J)-CON(I-1,J))*XZ2(I)
      A2(I,J)=CON(I,J)*XZ3(I)+BLOOD(I)*CB/2.
      A3(I,J)=CON(I,J)*XZ4(I)-(CON(I+1,J)-CON(I-1,J))*XZ2(I)
   23 CONTINUE
      DO 25 I=1,L1
      B1(I,1)=0.
      B2(I,1)=(CON(I,2)+CON(I,1))/(R(2)*R(2))+BLOOD(I)*CB/2.
      B3(I,1)=(CON(I,2)+CON(I,1))/(R(2)*R(2))
      DO 25 J=2,L2
      B1(I,J)=CON(I,J)*XR1(J)+(CON(I,J+1)-CON(I,J-1))*XR2(J)
      B2(I,J)=CON(I,J)*XR3(J)+BLOOD(I)*CB/2.
      B3(I,J)=CON(I,J)*XR4(J)-(CON(I,J+1)-CON(I,J-1))*XR2(J)
   25 CONTINUE
      DO 26 J=1,L2
   26 B2(1,J)=B2(1,J)+H/DZ
      RETURN
      END
```

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```
      -------------SUBROUTINE HTDEP-------------
C *** HTDEP COMPUTES RATES OF ENERGY DEPOSITION AT EACH GRID POINT PER
C *** UNIT VOLUME OF TISSUE
      COMMON ABS(11),ABSC,ALPHA,A1(35,35),A2(35,35),A3(35,35),B1(35,35),
     1B2(35,35),B3(35,35),BL(11),BLOOD(35),CB,CON1,CON2,CON(35,35),CUT,
     2D(35,35),DAM(2,2),DHF,DR,DT,DTX(200),DPULSE,DPULSC(50),DTEMP,DZ,
     3D0,D1,D2,D3,H,HAIR,HR(35),HW,IB,IHF,II,IMAX,IP,IPROF,IW,JMAX,K,KT,
     4LASER,LB,LMI,LNJ,LR,LZ,M,MK,M1,M3,N,N1,N3,NG,NGX,NPG(30),NPR(30),
     5NPULSE,NTP,NTX,NW,POW,POWER(200),POWERC(50),POWX,PX(50),R(35),RB,
     6REF,REPET,RIM,RGV,RN,RUNIF,RY(50),S(35,35),SHF,SH0,SH1,SH2,TB(11),
     7TDERM,TE,TEPID,TH(11),TOE,TSWEAT,TTIME,V(35,35),VHF,VO(35,35),
     8VSH(35,35),WATER(35,35),W0,W1,W2,W3,XC,XP(200),Z(35),ZBL,ZDEP,
     9ZM,ZR,ZW(10),ZZ,DR5,JW
      DIMENSION IE(11),IZ(36),ZE(11),ZH(36)
      REAL IE,IZ
      IF(K.GT.1)GO TO 32
      DO 4 I=1,M
      IZ(I)=0.
      DO 4 J=1,N
    4 S(I,J)=0.
      DO 5 I=1,M
    5 ZH(I)=(Z(I)+Z(I+1))/2.
      IE(1)=1.
      ZE(1)=0.
      L1=LZ+1
      DO 12 L=2,L1
      IE(L)=IE(L-1)*EXP(-ABS(L-1)*TH(L-1))
      IF(IE(L).LT.1.E-10)IE(L)=0.
   12 ZE(L)=ZE(L-1)+TH(L-1)
      IZ(1)=1.
      L=1
      LX=1
   14 IF(ZH(LX).LT.ZE(L+1))GO TO 16
      L=L+1
      GO TO 14
   16 IZ(LX+1)=IE(L)*EXP(-ABS(L)*(ZH(LX)-ZE(L)))
      LX=LX+1
      IF(LX.LE.M.AND.IZ(LX).GT.1.E-10)GO TO 14
      DO 20 I=1,LX
      X2=ZH(1)
      IF(I.GT.1)X2=ZH(I)-ZH(I-1)
      X3=(IZ(I)-IZ(I+1))/X2
      DO 20 J=1,N
   20 S(I,J)=X3*HR(J)
      IF(IHF.EQ.0)GO TO 54
      DO 22 I=IHF,M
   22 S(I,1)=0.
      S(IHF,1)=HR(1)*IZ(IHF)/SHF
      GO TO 54
C *** ADJUST S(I,J) FOR CHANGES IN ABSORPTIVITY
   32 LXX=AMAX1(LX,LMI)
      DO 42 J=1,LNJ
```

```
      DO 34 I=II,LXX
   34 S(I,J)=0.
      X0=IZ(II)
      XX=1.
      DO 36 I=II,LMI
      IF(X0.LT.1.E-10)GO TO 36
      X2=ZH(1)
      IF(I.GT.1)X2=ZH(I)-ZH(I-1)
      X1=XX*IZ(I+1)
      IF(D(I,J).GE.1.)X1=X0*EXP(-ABSC*X2)
      IF(X1.LT.1.E-10)X1=0.
      XX=X1/IZ(I+1)
      S(I,J)=HR(J)*(X0-X1)/X2
      IF(J.EQ.1.AND.I.EQ.IHF)X3=HR(1)*X0/SHF
      X0=X1
   36 CONTINUE
      L1=LMI+1
      IF(L1.GT.LXX)GO TO 42
      DO 37 I=L1,LXX
      IF(X0.LT.1.E-10)GO TO 37
      X1=XX*IZ(I+1)
      IF(X1.LT.1.E-10)X1=0.
      S(I,J)=HR(J)*(X0-X1)/(ZH(I)-ZH(I-1))
      IF(J.EQ.1.AND.I.EQ.IHF)X3=HR(1)*X0/SHF
      X0=X1
   37 CONTINUE
   42 CONTINUE
      IF(IHF.EQ.0)GO TO 54
      DO 44 I=IHF,M
   44 S(I,1)=0.
      S(IHF,1)=X3
   54 RETURN
      END
```

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```
      --------------SUBROUTINE TEMP--------------
C *** TEMP COMPUTES TEMPERATURES AT EACH GRID POINT ALLOWING FOR EVAPOR-
C *** ATION OF WATER
      COMMON ABS(11),ABSC,ALPHA,A1(35,35),A2(35,35),A3(35,35),B1(35,35),
     1B2(35,35),B3(35,35),BL(11),BLOOD(35),CB,CON1,CON2,CON(35,35),CUT,
     2D(35,35),DAM(2,2),DHF,DR,DT,DTX(200),DPULSE,DPULSC(50),DTEMP,DZ,
     3DO,D1,D2,D3,H,HAIR,HR(35),HW,IB,IHF,II,IMAX,IP,IPROF,IW,JMAX,K,KT,
     4LASER,LB,LMI,LNJ,LR,LZ,M,MK,M1,M3,N,N1,N3,NG,NGX,NPG(30),NPR(30),
     5NPULSE,NTP,NTX,NW,POW,POWER(200),POWERC(50),POWX,PX(50),R(35),RB,
     6REF,REPET,RIM,RGV,RN,RUNIF,RX(50),S(35,35),SHF,SH0,SH1,SH2,TB(11),
     7TDERM,TE,TEPID,TH(11),TOE,TSWEAT,TTIME,V(35,35),VHF,VO(35,35),
     8VSH(35,35),WATER(35,35),W0,W1,W2,W3,XC,XP(200),Z(35),ZBL,ZDEP,
     9ZM,ZR,ZW(10),ZZ,DR5,JW
      DIMENSION CXC(35),DXC(35),FXC(35),CXR(35),DXR(35),FXR(35),JM(35),
     1JSW(35,35),SW(35,35),VS(35,35),VXX(35,35),ZSW(35,35)
      IMAX=0
      JMAX=0
      IF(K.GT.1)GO TO 3
      IKW=NW-1
      DO 2 I=1,M
      JM(I)=0
      DO 2 J=1,N
      JSW(I,J)=0
    2 SW(I,J)=0.
      XW=100.-TE
      VHF=TOE
    3 DO 4 I=1,M
      DO 4 J=1,N
    4 VO(I,J)=V(I,J)
      KW=0
C *** COLUMNS(NORMAL)------------------
    9 DO 45 I=1,M
      DO 44 J=1,N
      W=2.*VSH(I,J)/DT
      FXC(J)=W+B2(I,J)
      IF(J.GT.1)FXC(J)=FXC(J)+B1(I,J)*CXC(J-1)
      CXC(J)=-B3(I,J)/FXC(J)
      SUM=(W-A2(I,J))*V(I,J)+A3(I,J)*V(I+1,J)+POW*S(I,J)-SW(I,J)
      IF(I.GT.1)SUM=SUM+A1(I,J)*V(I-1,J)
      IF(J.EQ.N)SUM=SUM+B3(I,J)*TOE
      DXC(J)=SUM/FXC(J)
      IF(J.GT.1)DXC(J)=(SUM+B1(I,J)*DXC(J-1))/FXC(J)
   44 CONTINUE
      VX=0.
      DO 45 L=1,N
      J=N+1-L
      VX=DXC(J)-CXC(J)*VX
   45 VXX(I,J)=VX
C *** ROWS(NORMAL)----------------------
      DO 50 J=1,N
      DO 48 I=1,M
      W=2.*VSH(I,J)/DT
      FXR(I)=W+A2(I,J)
      IF(I.GT.1)FXR(I)=FXR(I)+A1(I,J)*CXR(I-1)
      CXR(I)=-A3(I,J)/FXR(I)
      SUM=(W-B2(I,J))*VXX(I,J)+B3(I,J)*VXX(I,J+1)+POW*S(I,J)-SW(I,J)
      IF(J.GT.1)SUM=SUM+B1(I,J)*VXX(I,J-1)
      IF(I.EQ.M)SUM=SUM+A3(I,J)*TOE
```

```
      DXR(I)=SUM/FXR(I)
      IF(I.GT.1)DXR(I)=(SUM+A1(I,J)*DXR(I-1))/FXR(I)
   48 CONTINUE
      VX=0.
      DO 50 L=1,M
      I=M+1-L
      VX=DXR(I)-CXR(I)*VX
      IF(VX.LT.TOE)VX=TOE
      IF(I.GE.IP.OR.KW.GT.0)GO TO 50
C   * STEAM ESCAPES
      IF(VX.LT.XW.OR.WATER(I,J).LT..0001)GO TO 50
      IMAX=AMAX1(IMAX,I)
      IF(J.GT.JM(I))JM(I)=J
   50 V(I,J)=VX
      IF(IMAX.EQ.0)GO TO 90
      KW=KW+1
      IF(KW.GT.1)GO TO 52
      LX=IMAX
      DO 51 I=1,LX
      L1=JM(I)
      DO 51 J=1,L1
      IF(S(I,J).GT.(V(I,J)-XW)*VSH(I,J)/DT)JSW(I,J)=1
   51 CONTI UE
   52 IF(KW.GT.NW)GO TU 63
      DO 60 I=1,LX
      L1=JM(I)
      DO 60 J=1,L1
      IF(WATER(I,J).LT..001)GO TO 60
      X1=(V(I,J)-XW)*VSH(I,J)/DT
      X2=539.*WATER(I,J)/DT
      X3=SW(I,J)
      IF(KW.EQ.1.OR.KW.GE.IKW)GO TO 55
      X0=VS(I,J)-V(I,J)
      IF(JSW(I,J).EQ.0.OR.X0*X0.LT.1.)GO TO 55
      X4=ZW(KW)*(V(I,J)-XW)*ZSW(I,J)/(VS(I,J)-V(I,J))
      IF(X3+X4.LT.X1)X4=X1-X3
      GO TO 57
   55 X4=ZW(KW)*X1
   57 SW(I,J)=X3+X4
      IF(SW(I,J).LT.0.)SW(I,J)=0.
      IF(SW(I,J).GT.X2)SW(I,J)=X2
      ZSW(I,J)=SW(I,J)-X3
      VS(I,J)=V(I,J)
   60 CONTINUF
      DO 62 I=1,M
      DO 62 J=1,N
   62 V(I,J)=VO(I,J)
      GO TO 9
C *** CORRECT FOR EFFECTS OF WATER LOSS
   63 DO 65 I=1,LX
      L1=JM(I)
      DO 64 J=1,L1
      WATER(I,J)=WATER(I,J)-SW(I,J)*DT/539.
      IF(WATER(I,J).LT..001)WATER(I,J)=0.
      JSW(I,J)=0
   64 SW(I,J)=0.
      JM(I)=0
   65 JMAX=AMAX1(JMAX,L1)
      IF(NGX.EQ.0.OR.LASER.EQ.2)GO TO 90
      IF(POWER(K+1).GT.1.E-10)GO TO 90
C   * RESET TO SINGLE NON-CODED PULSES TO HANDLE WATER LOSS
      L1=ITIME*REPET+1.
```

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```
      KP=NPULSE-L1
      X0=SHF
      IF(ZM.LT.DHF)X0=1.E+10
      X1=AMIN1(DH,DZ,X0)
      DTL=ZR*X1*X1/ALPHA
      L1=K+1
      DO 72 L2=L1,MK
      POWER(L2)=0.
   72 XP(L2)=1.
      XX2=1./REPET-DPULSE
      XX4=XX2/(XC+1.)
      XX5=XC-1.
      XX6=ALOG(XC)
      LK=K
   74 IF(KP.LT.1)GO TO 82
      K0=LK
      IF(XX4.GT.DTO)GO TO 76
      LK=LK+1
      DTX(LK)=XX4
      LK=LK+1
      DTX(LK)=XX2-XX4
      GO TO 79
   76 L1=ALOG(XX2*XX5/DTO+1.)/XX6+1.
      DT2=XX2*XX5/(XC**L1-1.)
      L2=LK+1
      L3=LK+L1
      DO 78 LK=L2,L3
      DTX(LK)=DT2
   78 DT2=XC*DT2
      LK=L3
   79 DTU=ZZ*DTO
      NP=DPULSE/DTU
      IF(NP.LT.2)NP=2
      XX1=DPULSE/NP
      L2=LK+1
      L3=LK+NP
      DO 80 LK=L2,L3
      DTX(LK)=XX1
   80 POWER(LK)=POWX
      LK=L3
      KP=KP-1
      IF(2*LK+NTX-K0.LT.MK)GO TO 74
      WRITE(6,81)KP
   81 FORMAT(1H ,46HNUMBER OF PULSES TREATED LESS THAN NPULSE, KP=,I3)
   82 L2=LK+1
      L3=LK+NTX
      DO 84 LK=L2,L3
      DTX(LK)=DTU
   84 DTU=XC*DTO
      KT=L3
      NGX=0
C *** ASSESS MAXIMUM TEMPERATURES ACHIEVED, RGV(ANY LOCATION), RW(SUPER-
C ***  HEATED WATER), AND VHF(HAIR FOLLICLE)
   90 DO 92 I=1,M
      DO 92 J=1,N1
      IF(V(I,J).GT.RGV)RGV=V(I,J)
      IF(I.LT.IP.OR.V(I,J).LT.XW)GO TO 92
C *   STEAM CONTAINED
      IF(RW.GT.V(I,J))GO TO 92
      IH=I
```

```
      RB=V(I,J)
   V2 CONTINUE
      IF(IHF.GT.0)VHF=AMAX1(VHF,V(IHF,1))
      RETURN
      END
```

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```
      -------------SUBROUTINE DAMAGE-------------
C *** DAMAGE COMPUTES CUMMULATIVE THERMAL DAMAGE AT EACH GRID POINT
      COMMON ABS(11),ABSC,ALPHA,A1(35,35),A2(35,35),A3(35,35),B1(35,35),
     1B2(35,35),B3(35,35),BL(11),BLOOD(35),CB,CON1,CON2,CON(35,35),CUT,
     2D(35,35),DAM(2,2),DHF,DR,DT,DTX(200),DPULSE,DPULSC(50),DTEMP,DZ,
     3D0,D1,D2,D3,H,HAIR,HR(35),HW,IB,IMF,II,IMAX,IP,IPROF,IW,JMAX,K,KT,
     4LASER,LB,LMI,LNJ,LR,LZ,M,MK,M1,M3,N,N1,N3,NB,NBX,NPB(30),NPR(30),
     5NPULSE,NTP,NTX,NW,POW,POWER(200),POWERC(50),POWX,PX(50),R(35),RR,
     6REF,REPET,RIM,RGV,RN,RUNIF,RX(50),S(35,35),SHF,SH0,SH1,SH2,TB(11),
     7TDERM,TE,TEPID,TH(11),TOE,TSWEAT,TTIME,V(35,35),VHF,VO(35,35),
     8VSH(35,35),WATER(35,35),W0,W1,W2,W3,XC,XP(200),Z(35),ZBL,ZOEP,
     9ZM,ZN,ZW(10),ZZ,DH5,JW
      DO 4 L=K,KT
      IF(POWER(L).GT.1.E-10)KTO=L
    4 CONTINUE
      IF(K.GT.1)GO TO 6
      JW=1
      ZC1=DAM(1,1)
      ZE1=DAM(1,2)
      ZC2=DAM(2,1)
      ZE2=DAM(2,2)
      XD=44.-TE
    6 LMI=0
      LNJ=0
      IF(XP(K).LT..5)GO TO 28
      LL=0
      IF(K.LE.KTO)LL=1
C *** EVALUATE I,J INDICES AT WHICH THERMAL DAMAGE IS OCCURRING
      ID=0
      JD=0
      DO 12 I=1,M
      DO 12 J=1,N
      IF(V(I,J).LT.XD)GO TO 12
      ID=I
      JD=AMAX1(JD,J)
   12 CONTINUE
C *** REVISE MATRIX ELEMENTS IF BLISTER FORMS AT VARIOUS R(J)
      I=IW
      L1=JW
      DO 14 J=JW,N
      IF(V(I,J)+TE.LT.DTEMP)GO TO 14
      IF(IW.GT.2)GO TO 13
      A2(1,J)=(H+2.*HW)/DZ+BLOOD(1)*CB/2.
      A3(1,J)=2.*HW/DZ
      A1(2,J)=2.*HW/Z(3)
      A2(2,J)=2.*HW/Z(3)+(CON(2,J)+CON(3,J))/(Z(3)*(Z(3)-Z(2)))+BLOOD(2)
     1*CB/2.
      A3(2,J)=(CON(2,J)+CON(3,J))/(Z(3)*(Z(3)-Z(2)))
      L1=J+1
      GO TO 14
   13 A1(I-1,J)=2.*CON(I-1,J)/((Z(I)-Z(I-2))*(Z(I-1)-Z(I-2)))
      A2(I-1,J)=2.*CON(I-1,J)/((Z(I)-Z(I-2))*(Z(I-1)-Z(I-2)))+BLOOD(I-1)
     1*CB/2.+2.*HW/(Z(I)-Z(I-2))
      A3(I-1,J)=2.*HW/(Z(I)-Z(I-2))
      A1(I,J)=2.*HW/(Z(I+1)-Z(I-1))
      A2(I,J)=2.*CON(I,J)/((Z(I+1)-Z(I-1))*(Z(I+1)-Z(I)))+BLOOD(I)*CB/2.
     1+2.*HW/(Z(I+1)-Z(I-1))
      A3(I,J)=2.*CON(I,J)/((Z(I+1)-Z(I-1))*(Z(I+1)-Z(I)))
      L1=J+1
   14 CONTINUE
```

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```
      JW=L1
      IF(ID.LT.I1)GO TO 28
C *** EVALUATE THERMAL DAMAGE AT EACH GRID POINT OF LIVE TISSUES
      DO 22 I=I1,ID
      DO 22 J=1,JD
      X1=.5*(V(I,J)+VO(I,J))+TE
      IF(X1.LT.44.)GO TO 22
      IF(X1.LT.50.)X2=ZC1-ZE1/(X1+273.)
      IF(X1.GE.50.)X2=ZC2-ZE2/(X1+273.)
      IF(X2.GT.60.)X2=60.
      X3=XP(K)*DT*EXP(X2)
      IF(LL.EQ.1)GO TO 20
      IF(D(I,J).LT.1..AND.X3.GT..05)LL=1
   20 D(I,J)=D(I,J)+X3
      IF(D(I,J).GT.1.E+20)D(I,J)=1.E+20
      IF(D(I,J).GE.1.)LMI=AMAX1(LMI,I)
      IF(D(I,J).GE.1.)LNJ=AMAX1(LNJ,J)
   22 CONTINUE
      IF(LL.EQ.0.AND.K.GT.KT-NTX+5)KT=K
      WRITE(6,24)LMI,LNJ,ID,JD
   24 FORMAT(1H ,4HLMI=,I3,2X,4HLNJ=,I3,2X,3HID=,I3,2X,3HJD=,I3)
   28 RETURN
      END
```

```
-------------DATA CARDS(SET 1,SINGLE RUBY PULSE)---------------

    -------------DATA CARD NUMBER 1-----------------
    3   1.+1 1.33-4 1.36-3  2.2-1  3.7-1  6.3-1  9.5-1   2.-1   8.-1   5.-2
    -------------DATA CARD NUMBER 2-----------------
1.05+0   5.-1 1.03+0  9.8-1 1.21-2   6.-3 1.31+2   1.+2   2.-2
    -------------DATA CARD NUMBER 3-----------------
 .0135  .0978    3.0
    -------------DATA CARD NUMBER 4-----------------
  1.0      0.  .0118     0.
    -------------DATA CARD NUMBER 5-----------------
   0.  .0060  .0121  .1779    37.    22.   .006
    -------------DATA CARD NUMBER 6-----------------
 149. 50000.   242. 80000.
    -------------DATA CARDS NUMBER 7-----------------
100.0  119.6  132.9  142.9  151.1  158.1  164.2  169.5  174.5  179.0
183.2  187.1  190.7  194.1  197.4  200.4  203.4  206.1  208.8  211.4
213.9  216.2  218.5  220.8  222.9  225.0  227.0
    -------------DATA CARD NUMBER 8-----------------
    3  1.2+1  2.0-4  7.0-4   0.+0  6.0-1
    -------------DATA CARD NUMBER 9-----------------
 .048  .1420    3.0
    -------------DATA CARD NUMBER 10----------------
 17.      7.     10.
    -------------DATA CARD NUMBER 11----------------
   1    100
    -------------DATA CARD NUMBER 12,GAUSS----------
  .17   .135      5     15
    -------------DATA CARD NUMBER 13----------------
 .694   1.30     .5   1.00      1      1      0     20
    -------------DATA CARD NUMBER 14,NC,1-----------
   20   5.-4 3.48+3
    -------------DATA CARD NUMBER 15----------------
   15
    -------------DATA CARD NUMBER 16----------------
    1      7      1      7      1      0      1
    -------------DATA CARD NUMBER 17----------------
 0.+0
    -------------DATA CARD NUMBER 18----------------
 1.+2
    -------------DATA CARD NUMBER 19----------------
    4  1.0+0  1.0+0  1.0+0  1.0+0
    -------------DATA CARD NUMBER 20----------------
 1.-1  1.0+0  1.0+4  4.0+2
```

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```
OXQT.F E.MAINA
 Z=  1.00  1.00  1.00  1.00

 DB1=  .1000+00  .1000+1  .1000+05  .4000+3
 DTX=
   .250-04   .250-04   .250-04   .250-04   .250-04   .250-04   .250-04   .250-04
   .250-04   .250-04   .250-04   .250-04   .250-04   .250-04   .250-04   .250-04
   .250-04   .250-04   .250-04   .250-04   .336-01   .437-01   .568-01   .739-01
   .960-01   .125+00   .162+00   .211+00   .274+00   .357+00   .464+00   .603+00
   .783+00   .102+01   .132+01   .172+01   .224+01   .291+01   .378+01   .492+01
 POWER=
   .348+04   .348+04   .348+04   .348+04   .348+04   .348+04   .348+04   .348+04
   .348+04   .348+04   .348+04   .348+04   .348+04   .348+04   .348+04   .348+04
   .348+04   .348+04   .348+04   .348+04   .000      .000      .000      .000
   .000      .000      .000      .000      .000      .000      .000      .000
   .000      .000      .000      .000      .000      .000      .000      .000
 XP=
        1.        1.        1.        1.        1.        1.        1.        1.
        1.        1.        1.        1.        1.        1.        1.        1.
        1.        1.        1.        1.        1.        1.        1.        1.
        1.        1.        1.        1.        1.        1.        1.        1.
        1.        1.        1.        1.        1.        1.        1.        1.
 R=
     .0000     .0340     .0680     .1020     .1360     .1700     .2040     .2380
     .2720     .3060     .3400     .3740     .4080     .4420     .4760     .5100
 Z=
     .0000     .0121     .0301     .0569     .0967     .1560     .2442     .3753
     .5705     .8608    1.2927    1.9353    2.8912    4.3133    6.4289    9.5763

 SIGMA= .170+00
 HR=
   .211+01   .195+01   .153+01   .103+01   .585+00   .285+00   .118+00   .416-01
   .125-01   .321-02   .709-03   .130-03   .206-04   .279-05   .320-06
 ABSC=    12.  ABSW=    10.  CB=  1.000  CON1=  .00013  CON2=  .00136
 D0= 1.050  D1=  .500  D2= 1.030  D3=  .980  DEPID=  .0060
 HAIR=   .00  REF=   .60  SH0=  .2200  SH1=  .3700  SH2=  .6300
 TDERM=  .1779  TE=  22.  TEPID=  .0121  TO=  37.  TSWEAT=  .0000
 W0=  .950  W1=  .200  W2=  .800  W3=  .050  WAVEL=  .694
 XC= 1.300  ZDEP=  .006  ZR=   .5  ZZ=   1.00
 IPHOF=1  LASER=1  LB= 3  LZ= 3  N=15  N1= 5  M=15  M1= 1
 NPULSE=   1  NGX=0  NTX=20
 ZBL= .121-01  HW= .600-02  DTEMP=  131.  DHF= .100+03
 SHF= .200-01
 CUT=   .1350  RIM=   .1700
 DPULSE=  .500-03  NTP=20  POWX=  .348+04
 ID1= 1  ID2= 7  ITYPE= 1  JD1= 1  JD2= 7  KTYPE=0
 TIME1-2=
  .000    .100+03
 TH=
   .0480  .1420 3.0000
 ABS=
    17.     7.    10.
 TB=
   .0135  .0978 3.0000
 BL=
   .0000  .0118  .0000
 DAM(1,1)= 149.0  DAM(1,2)=50000.  DAM(2,1)= 242.0  DAM(2,2)=80000.
```

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```
DR= .0340  RN=   .4061  DZ= .0121  ZM=  9.5763  NG= 0
CON=
    .0011     .0012     .0012     .0012     .0012     .0012     .0002     .0002
    .0002     .0002     .0002     .0002     .0002     .0002     .0002     .0002
VBM=
    .7416     .8851     .8851     .8851     .8851     .8851     .3941     .3941
    .3941     .3941     .3941     .3941     .3941     .3941     .3941     .3941
HEAT DEPOSITION RATES=----------
           R=    .0000    .0340    .0680    .1020    .1360    .1700    .2040
Z=    .0000    .341+02 .314+02 .247+02 .166+02 .946+01 .460+01 .191+01
Z=    .0121    .285+02 .263+02 .207+02 .139+02 .792+01 .385+01 .160+01
Z=    .0301    .208+02 .192+02 .151+02 .101+02 .578+01 .281+01 .117+01
Z=    .0569    .734+01 .678+01 .533+01 .357+01 .204+01 .991+00 .411+00
Z=    .0967    .451+01 .416+01 .327+01 .219+01 .125+01 .609+00 .252+00
Z=    .1560    .308+01 .284+01 .223+01 .150+01 .854+00 .415+00 .172+00
Z=    .2442    .190+01 .175+01 .138+01 .922+00 .526+00 .256+00 .106+00

DT= .250-04   TIME= .2500-04   POWER=   .348+04   XP=    1.   IMAX=15   JMAX=15
           R=     .0000     .0340     .0680     .1020     .1360     .1700     .2040
Z=    .0000         4.0       3.7       2.9       1.9       1.1        .5        .2
Z=    .0121         2.8       2.6       2.0       1.8        .8        .4        .2
Z=    .0301         2.0       1.9       1.5       1.0        .6        .3        .1
Z=    .0569          .7        .7        .5        .4        .2        .1        .0
Z=    .0967          .4        .4        .3        .2        .1        .1        .0
Z=    .1560          .3        .3        .2        .1        .1        .0        .0
Z=    .2442          .4        .4        .3        .2        .1        .1        .0

DT= .250-04   TIME= .5000-04   POWER=   .348+04   XP=    1.   IMAX= 0   JMAX= 0
           R=     .0000     .0340     .0680     .1020     .1360     .1700     .2040
Z=    .0000         8.0       7.4       5.8       3.9       2.2       1.1        .4
Z=    .0121         5.6       5.2       4.1       2.7       1.6        .8        .3
Z=    .0301         4.1       3.8       3.0       2.0       1.1        .6        .2
Z=    .0569         1.4       1.3       1.0        .7        .4        .2        .1
Z=    .0967          .9        .8        .6        .4        .2        .1        .0
Z=    .1560          .6        .6        .4        .3        .2        .1        .0
Z=    .2442          .8        .8        .6        .4        .2        .1        .0

DT= .250-04   TIME= .7500-04   POWER=   .348+04   XP=    1.   IMAX= 0   JMAX= 0
LMI=  0   LNJ=  0   ID=  2   JD=  3
           R=     .0000     .0340     .0680     .1020     .1360     .1700     .2040
Z=    .0000        12.0      11.1       8.7       5.8       3.3       1.6        .7
Z=    .0121         8.4       7.8       6.1       4.1       2.3       1.1        .5
Z=    .0301         6.1       5.7       4.5       3.0       1.7        .8        .3
Z=    .0569         2.2       2.0       1.6       1.1        .6        .3        .1
Z=    .0967         1.3       1.2       1.0        .6        .4        .2        .1
Z=    .1560          .9        .8        .7        .4        .3        .1        .1
Z=    .2442         1.3       1.2        .9        .6        .3        .2        .1

DT= .250-04   TIME= .1000-03   POWER=   .348+04   XP=    1.   IMAX= 0   JMAX= 0
LMI=  0   LNJ=  0   ID=  3   JD=  4
           R=     .0000     .0340     .0680     .1020     .1360     .1700     .2040
Z=    .0000        16.0      14.8      11.6       7.8       4.4       2.2        .9
Z=    .0121        11.2      10.4       8.1       5.5       3.1       1.5        .6
Z=    .0301         8.2       7.6       5.9       4.0       2.3       1.1        .5
Z=    .0569         2.9       2.7       2.1       1.8        .8        .4        .2
Z=    .0967         1.8       1.6       1.3        .9        .5        .2        .1
Z=    .1560         1.2       1.1        .9        .6        .3        .2        .1
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Z=	.2442	1.7	1.5	1.2	.8	.5	.2	.1

DT= .250-04 TIME= .1250-03 POWER= .348+04 XP= 1. IMAX= 0 JMAX= 0
LMI= 0 LNJ= 0 ID= 3 JD= 4

R=		.0000	.0340	.0680	.1020	.1360	.1700	.2040
Z=	.0000	20.0	18.4	14.5	9.7	5.5	2.7	1.1
Z=	.0121	14.0	12.9	10.2	6.8	3.9	1.9	.8
Z=	.0301	10.2	9.4	7.4	5.0	2.8	1.4	.6
Z=	.0569	3.6	3.3	2.6	1.8	1.0	.5	.2
Z=	.0967	2.2	2.0	1.6	1.1	.6	.3	.1
Z=	.1560	1.5	1.4	1.1	.7	.4	.2	.1
Z=	.2442	2.1	1.9	1.5	1.0	.6	.3	.1

DT= .250-04 TIME= .1500-03 POWER= .348+04 XP= 1. IMAX= 0 JMAX= 0
LMI= 0 LNJ= 0 ID= 3 JD= 4

R=		.0000	.0340	.0680	.1020	.1360	.1700	.2040
Z=	.0000	24.0	22.1	17.4	11.7	6.7	3.2	1.3
Z=	.0121	16.8	15.5	12.2	8.2	4.7	2.3	.9
Z=	.0301	12.3	11.3	8.9	6.0	3.4	1.7	.7
Z=	.0569	4.3	4.0	3.1	2.[illegible]	1.2	.6	.2
Z=	.0967	2.7	2.5	1.9	1.3	.7	.4	.1
Z=	.1560	1.8	1.7	1.3	.9	.5	.2	.1
Z=	.2442	2.5	2.3	1.8	1.2	.7	.3	.1

DT= .250-04 TIME= .1750-03 POWER= .348+04 XP= 1. IMAX= 0 JMAX= 0
LMI= 0 LNJ= 0 ID= 3 JD= 5

R=		.0000	.0340	.0680	.1020	.1360	.1700	.2040
Z=	.0000	28.0	25.8	20.3	13.6	7.8	3.8	1.6
Z=	.0121	19.6	18.1	14.3	9.6	5.5	2.7	1.1
Z=	.0301	14.3	13.2	10.4	7.0	4.0	1.9	.8
Z=	.0569	5.1	4.7	3.7	2.5	1.4	.7	.3
Z=	.0967	3.1	2.9	2.3	1.5	.9	.4	.2
Z=	.1560	2.1	2.0	1.5	1.0	.6	.3	.1
Z=	.2442	2.9	2.7	2.1	1.4	.8	.4	.2

DT= .250-04 TIME= .2000-03 POWER= .348+04 XP= 1. IMAX= 0 JMAX= 0
LMI= 0 LNJ= 0 ID= 3 JD= 5

R=		.0000	.0340	.0680	.1020	.1360	.1700	.2040
Z=	.0000	32.0	29.5	23.2	15.5	8.9	4.3	1.8
Z=	.0121	22.4	20.7	16.3	10.9	6.2	3.0	1.3
Z=	.0301	16.4	15.1	11.9	8.0	4.5	2.2	.9
Z=	.0569	5.8	5.3	4.2	2.8	1.6	.8	.3
Z=	.0957	3.5	3.3	2.6	1.7	1.0	.5	.2
Z=	.1560	2.4	2.2	1.8	1.2	.7	.3	.1
Z=	.2442	3.3	3.1	2.4	1.6	.9	.5	.2

DT= .250-04 TIME= .2250-03 POWER= .348+04 XP= 1. IMAX= 0 JMAX= 0
LMI= 0 LNJ= 0 ID= 3 JD= 5

R=		.0000	.0340	.0680	.1020	.1360	.1700	.2040
Z=	.0000	35.9	33.2	26.1	17.5	10.0	4.9	2.0
Z=	.0121	25.3	23.3	18.3	12.3	7.0	3.4	1.4
Z=	.0301	18.4	17.0	13.4	9.0	5.1	2.5	1.0
Z=	.0569	6.5	6.0	4.7	3.2	1.8	.9	.4
Z=	.0967	4.0	3.7	2.9	1.9	1.1	.5	.2
Z=	.1560	2.7	2.5	2.0	1.3	.8	.4	.2
Z=	.2442	3.6	3.5	2.7	1.8	1.0	.5	.2

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```
DT= .250-04  TIME= .2500-03  POWER=   .348+04  XP=    1.  IMAX= 0  JMAX= 0
LMI=  0  LNJ=  0  ID=  4  JD=  5
            R=    .0000    .0340    .0680    .1020    .1360    .1700    .2040
Z=    .0000        39.9     36.9     29.0     19.4     11.1      5.4      2.2
Z=    .0121        28.1     25.9     20.4     13.6      7.8      3.8      1.6
Z=    .0301        20.5     18.9     14.9     10.0      5.7      2.8      1.1
Z=    .0569         7.2      6.7      5.2      3.5      2.0      1.0       .4
Z=    .0967         4.4      4.1      3.2      2.2      1.2       .6       .2
Z=    .1560         3.0      2.8      2.2      1.5       .8       .4       .2
Z=    .2442         4.2      3.9      3.0      2.0      1.2       .6       .2

DT= .250-04  TIME= .2750-03  POWER=   .348+04  XP=    1.  IMAX= 0  JMAX= 0
LMI=  0  LNJ=  0  ID=  4  JD=  5
            R=    .0000    .0340    .0680    .1020    .1360    .1700    .2040
Z=    .0000        43.9     40.5     31.9     21.4     12.2      5.9      2.5
Z=    .0121        30.9     28.5     22.4     15.0      8.6      4.2      1.7
Z=    .0301        22.5     20.8     16.3     11.0      6.3      3.0      1.3
Z=    .0569         7.9      7.3      5.8      3.9      2.2      1.1       .4
Z=    .0967         4.9      4.5      3.5      2.4      1.4       .7       .3
Z=    .1560         3.3      3.1      2.4      1.6       .9       .4       .2
Z=    .2442         4.6      4.2      3.3      2.2      1.3       .6       .3

DT= .250-04  TIME= .3000-03  POWER=   .348+04  XP=    1.  IMAX= 0  JMAX= 0
LMI=  0  LNJ=  0  ID=  4  JD=  5
            R=    .0000    .0340    .0680    .1020    .1360    .1700    .2040
Z=    .0000        47.9     44.2     34.6     23.3     13.3      6.5      2.7
Z=    .0121        33.7     31.1     24.4     16.4      9.3      4.5      1.9
Z=    .0301        24.6     22.7     17.8     11.9      6.8      3.3      1.4
Z=    .0569         8.7      8.0      6.3      4.2      2.4      1.2       .5
Z=    .0967         5.3      4.9      3.9      2.6      1.5       .7       .3
Z=    .1560         3.6      3.3      2.6      1.8      1.0       .5       .2
Z=    .2442         5.0      4.6      3.6      2.4      1.4       .7       .3

DT= .250-04  TIME= .3250-03  POWER=   .348+04  XP=    1.  IMAX= 0  JMAX= 0
LMI=  0  LNJ=  0  ID=  4  JD=  6
            R=    .0000    .0340    .0680    .1020    .1360    .1700    .2040
Z=    .0000        51.9     47.9     37.7     25.2     14.4      7.0      2.9
Z=    .0121        36.5     33.7     26.5     17.7     10.1      4.9      2.0
Z=    .0301        26.6     24.6     19.3     12.9      7.4      3.6      1.5
Z=    .0569         9.4      8.7      6.8      4.6      2.6      1.3       .5
Z=    .0967         5.8      5.3      4.2      2.8      1.6       .8       .3
Z=    .1560         3.9      3.6      2.9      1.9      1.1       .5       .2
Z=    .2442         5.4      5.0      3.9      2.6      1.5       .7       .3

DT= .250-04  TIME= .3500-03  POWER=   .348+04  XP=    1.  IMAX= 0  JMAX= 0
LMI=  2  LNJ=  1  ID=  4  JD=  6
            R=    .0000    .0340    .0680    .1020    .1360    .1700    .2040
Z=    .0000        55.9     51.6     40.6     27.2     15.5      7.5      3.1
Z=    .0121        39.3     36.3     28.5     19.1     10.9      5.3      2.2
Z=    .0301        28.7     26.5     20.8     13.9      8.0      3.9      1.6
Z=    .0569        10.1      9.3      7.3      4.9      2.8      1.4       .6
Z=    .0967         6.2      5.7      4.5      3.0      1.7       .8       .3
Z=    .1560         4.2      3.9      3.1      2.1      1.2       .6       .2
Z=    .2442         5.9      5.4      4.3      2.8      1.6       .8       .3

DT= .250-04  TIME= .3750-03  POWER=   .348+04  XP=    1.  IMAX= 0  JMAX= 0
LMI=  2  LNJ=  2  ID=  4  JD=  6
```

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R=	.0000	.0340	.0680	.1020	.1360	.1700	.2040
Z= .0000	59.9	55.3	43.5	29.1	16.6	8.1	3.3
Z= .0121	41.3	38.9	30.6	20.5	11.7	5.7	2.4
Z= .0301	30.9	28.3	22.3	14.9	8.5	4.1	1.7
Z= .0569	10.9	10.0	7.9	5.3	3.0	1.5	.6
Z= .0967	6.7	6.1	4.8	3.2	1.8	.9	.4
Z= .1560	4.6	4.2	3.3	2.2	1.3	.6	.3
Z= .2442	6.3	5.8	4.6	3.1	1.7	.8	.4

DT= .250-04 TIME= .4000-03 POWER= .348+04 XP= 1. IMAX= 0 JMAX= 0
LMI= 2 LNJ= 2 ID= 5 JD= 6

R=	.0000	.0340	.0680	.1020	.1360	.1700	.2040
Z= .0000	63.0	59.0	46.4	31.1	17.7	8.6	3.6
Z= .0121	43.4	40.8	32.6	21.8	12.5	6.1	2.5
Z= .0301	33.1	30.4	23.8	15.9	9.1	4.4	1.8
Z= .0569	11.7	10.7	8.4	5.6	3.2	1.6	.6
Z= .0967	7.2	6.6	5.1	3.4	2.0	1.0	.4
Z= .1560	4.9	4.5	3.5	2.4	1.3	.7	.3
Z= .2442	6.8	6.2	4.9	3.3	1.9	.9	.4

DT= .250-04 TIME= .4250-03 POWER= .348+04 XP= 1. IMAX= 1 JMAX= 1
LMI= 2 LNJ= 2 ID= 7 JD= 6

R=	.0000	.0340	.0680	.1020	.1360	.1700	.2040
Z= .0000	63.0	62.6	49.3	33.0	18.8	9.2	3.8
Z= .0121	45.5	42.6	34.6	23.2	13.2	6.4	2.7
Z= .0301	35.3	32.4	25.3	16.9	9.7	4.7	1.9
Z= .0569	12.4	11.4	8.9	6.0	3.4	1.7	.7
Z= .0967	7.6	7.0	5.5	3.7	2.1	1.0	.4
Z= .1560	5.2	4.8	3.7	2.5	1.4	.7	.3
Z= .2442	7.2	6.6	5.2	3.5	2.0	1.0	.4

DT= .250-04 TIME= .4500-03 POWER= .348+04 XP= 1. IMAX= 1 JMAX= 1
LMI= 3 LNJ= 3 ID= 7 JD= 6

R=	.0000	.0340	.0680	.1020	.1360	.1700	.2040
Z= .0000	63.0	63.0	52.1	34.9	19.9	9.7	4.0
Z= .0121	47.5	44.5	[illegible]	24.6	14.0	6.8	2.8
Z= .0301	37.3	34.5	26.7	17.9	10.2	5.0	2.1
Z= .0569	13.2	12.2	9.4	6.3	3.6	1.8	.7
Z= .0967	8.1	7.5	5.8	3.9	2.2	1.1	.4
Z= .1560	5.5	5.1	4.0	2.6	1.5	.7	.3
Z= .2442	7.7	7.0	5.5	3.7	2.1	1.0	.4

DT= .250-04 TIME= .4750-03 POWER= .348+04 XP= 1. IMAX= 1 JMAX= 2
LMI= 3 LNJ= 3 ID= 7 JD= 6

R=	.0000	.0340	.0680	.1020	.1360	.1700	.2040
Z= .0000	63.0	63.0	55.0	36.9	21.1	10.2	4.2
Z= .0121	49.6	46.4	38.2	25.9	14.8	7.2	3.0
Z= .0301	39.1	36.5	28.4	18.9	10.8	5.3	2.2
Z= .0569	14.1	12.9	10.0	6.7	3.8	1.9	.8
Z= .0967	8.7	7.9	6.1	4.1	2.3	1.1	.5
Z= .1560	5.9	5.4	4.2	2.8	1.6	.8	.3
Z= .2442	8.2	7.5	5.8	3.9	2.2	1.1	.4

DT= .250-04 TIME= .5000-03 POWER= .348+04 XP= 1. IMAX= 1 JMAX= 2
LMI= 3 LNJ= 3 ID= 7 JD= 6

R=	.0000	.0340	.0680	.1020	.1360	.1700	.2040
Z= .0000	63.0	63.0	57.9	38.5	22.2	10.8	4.5

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Z= .0121	51.6	48.3	39.7	27.3	15.6	7.6	3.1
Z= .0301	40.8	38.0	30.0	19.9	11.4	5.5	2.3
Z= .0569	15.0	13.7	10.6	7.0	4.0	1.9	.8
Z= .0967	9.2	8.4	6.5	4.3	2.5	1.2	.5
Z= .1560	6.3	5.7	4.4	2.9	1.7	.8	.3
Z= .2442	8.7	7.9	6.1	4.1	2.3	1.1	.5

DT= .336-01 TIME= .3413-01 POWER= .000 XP= 1. IMAX= 1 JMAX= 2
LMI= 3 LNJ= 4 ID= 7 JD= 6

R=	.0000	.0340	.0680	.1020	.1360	.1700	.2040
Z= .0000	56.7	54.9	48.0	32.7	18.8	9.2	3.9
Z= .0121	51.5	48.6	40.6	27.9	16.0	7.9	3.3
Z= .0301	39.9	37.0	29.4	19.6	11.3	5.6	2.3
Z= .0569	15.9	14.5	11.3	7.5	4.3	2.1	.9
Z= .0967	9.2	8.4	6.5	4.3	2.5	1.2	.5
Z= .1560	6.3	5.7	4.4	3.0	1.7	.8	.3
Z= .2442	8.6	7.9	6.1	4.1	2.3	1.1	.5

DT= .437-01 TIME= .7785-01 POWER= .000 XP= 1. IMAX= 0 JMAX= 0
LMI= 3 LNJ= 4 ID= 7 JD= 6

R=	.0000	.0340	.0680	.1020	.1360	.1700	.2040
Z= .0000	52.6	49.9	42.4	29.2	17.0	8.4	3.6
Z= .0121	50.0	47.1	39.4	27.1	15.7	7.8	3.3
Z= .0301	39.0	36.1	28.9	19.6	11.4	5.6	2.4
Z= .0569	16.9	15.4	12.1	8.1	4.7	2.3	1.0
Z= .0967	9.3	8.4	6.5	4.4	2.5	1.2	.5
Z= .1560	6.3	5.7	4.4	3.0	1.7	.9	.4
Z= .2442	8.6	7.8	6.1	4.1	2.3	1.1	.5

DT= .568-01 TIME= .1347+00 POWER= .000 XP= 1. IMAX= 0 JMAX= 0
LMI= 3 LNJ= 4 ID= 7 JD= 6

R=	.0000	.0340	.0680	.1020	.1360	.1700	.2040
Z= .0000	49.2	46.2	38.7	26.8	15.8	7.9	3.4
Z= .0121	47.5	44.4	37.0	25.6	15.0	7.6	3.3
Z= .0301	37.8	34.9	28.3	19.4	11.3	5.7	2.4
Z= .0569	18.0	16.3	12.9	8.8	5.1	2.6	1.1
Z= .0967	9.4	8.4	6.6	4.5	2.6	1.3	.5
Z= .1560	6.3	5.7	4.4	3.0	1.7	.9	.4
Z= .2442	8.6	7.8	6.0	4.0	2.3	1.1	.5

DT= .739-01 TIME= .2096+00 POWER= .000 XP= 1. IMAX= 0 JMAX= 0
LMI= 3 LNJ= 4 ID= 7 JD= 6

R=	.0000	.0340	.0680	.1020	.1360	.1700	.2040
Z= .0000	45.9	42.6	35.4	24.8	14.7	7.5	3.3
Z= .0121	44.5	41.2	34.2	23.9	14.2	7.3	3.2
Z= .0301	36.4	33.4	27.2	18.9	11.2	5.7	2.5
Z= .0569	19.1	17.2	13.8	9.4	5.6	2.8	1.2
Z= .0967	9.5	8.5	6.7	4.6	2.7	1.4	.6
Z= .1560	6.3	5.6	4.4	3.0	1.8	.9	.4
Z= .2442	8.5	7.7	6.0	4.0	2.3	1.2	.5

DT= .960-01 TIME= .3046+00 POWER= .000 XP= 1. IMAX= 0 JMAX= 0
LMI= 3 LNJ= 4 ID= 7 JD= 6

R=	.0000	.0340	.0680	.1020	.1360	.1700	.2040
Z= .0000	42.1	38.7	32.1	22.7	13.7	7.2	3.2
Z= .0121	41.1	37.7	31.2	22.0	13.3	6.9	3.1
Z= .0301	34.6	31.6	25.9	18.1	10.9	5.7	2.6

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```
Z=   .0569      19.9    18.0    14.5    10.1     6.0     3.1     1.4
Z=   .0967       9.8     8.7     6.9     4.8     2.8     1.5      .6
Z=   .1560       6.3     5.6     4.4     3.1     1.8     1.0      .4
Z=   .2442       8.4     7.6     5.9     4.0     2.3     1.2      .5

DT= .125+00  TIME= .4295+00  POWER=  .000     XP=   1.  IMAX= 0  JMAX= 0
LMI=  3  LNJ=  4  ID=  7  JD=  5
           R=  .0000   .0340   .0680   .1020   .1360   .1700   .2040
Z=   .0000      38.1    34.7    28.7    20.5    12.7     6.8     3.1
Z=   .0121      37.3    34.0    28.1    20.0    12.4     6.6     3.1
Z=   .0301      32.3    29.3    24.1    17.2    10.6     5.6     2.6
Z=   .0569      20.5    18.4    15.0    10.6     6.5     3.4     1.6
Z=   .0967      10.1     9.0     7.2     5.0     3.1     1.6      .7
Z=   .1560       6.3     5.6     4.5     3.1     1.9     1.0      .5
Z=   .2442       8.3     7.5     5.9     4.0     2.3     1.2      .5

DT= .162+00  TIME= .5918+00  POWER=  .000     XP=   1.  IMAX= 0  JMAX= 0
LMI=  3  LNJ=  4  ID=  7  JD=  5
           R=  .0000   .0340   .0680   .1020   .1360   .1700   .2040
Z=   .0000      33.9    30.7    25.4    18.4    11.6     6.4     3.0
Z=   .0121      33.3    30.2    25.0    18.1    11.4     6.3     3.0
Z=   .0301      29.6    26.8    22.1    16.0    10.0     5.5     2.6
Z=   .0569      20.5    18.4    15.1    10.8     6.8     3.7     1.7
Z=   .0967      10.4     9.3     7.5     5.3     3.3     1.8      .8
Z=   .1560       6.3     5.6     4.5     3.2     2.0     1.1      .5
Z=   .2442       8.2     7.3     5.8     3.9     2.3     1.2      .5

DT= .211+00  TIME= .8028+00  POWER=  .000     XP=   1.  IMAX= 0  JMAX= 0
LMI=  3  LNJ=  4  ID=  7  JD=  5
           R=  .0000   .0340   .0680   .1020   .1360   .1700   .2040
Z=   .0000      29.6    26.7    22.2    16.3    10.6     6.0     3.0
Z=   .0121      29.2    26.4    21.9    16.1    10.4     5.9     2.9
Z=   .0301      26.6    24.0    19.9    14.6     9.4     5.3     2.6
Z=   .0569      19.9    17.8    14.7    10.8     6.9     3.9     1.9
Z=   .0967      10.8     9.6     7.8     5.7     3.6     2.0     1.0
Z=   .1560       6.3     5.6     4.6     3.3     2.1     1.2      .6
Z=   .2442       8.0     7.1     5.6     3.9     2.4     1.2      .6

DT= .274+00  TIME= .1077+01  POWER=  .000     XP=   1.  IMAX= 0  JMAX= 0
LMI=  3  LNJ=  4  ID=  7  JD=  5
           R=  .0000   .0340   .0680   .1020   .1360   .1700   .2040
Z=   .0000      25.3    22.8    19.1    14.3     9.5     5.6     2.9
Z=   .0121      25.1    22.6    18.9    14.2     9.4     5.6     2.9
Z=   .0301      23.3    21.0    17.6    13.1     8.7     5.1     2.6
Z=   .0569      18.6    16.7    13.9    10.3     6.9     4.0     2.0
Z=   .0967      10.9     9.8     8.1     6.0     3.9     2.3     1.1
Z=   .1560       6.4     5.7     4.7     3.5     2.3     1.3      .7
Z=   .2442       7.8     6.9     5.5     3.9     2.4     1.3      .6

DT= .357+00  TIME= .1434+01  POWER=  .000     XP=   1.  IMAX= 0  JMAX= 0
LMI=  3  LNJ=  4  ID=  7  JD=  5
           R=  .0000   .0340   .0680   .1020   .1360   .1700   .2040
Z=   .0000      21.2    19.2    16.2    12.4     8.5     5.2     2.8
Z=   .0121      21.1    19.1    16.1    12.3     8.4     5.2     2.8
Z=   .0301      19.9    18.0    15.2    11.6     7.9     4.9     2.6
Z=   .0569      16.7    15.0    12.7     9.6     6.6     4.0     2.1
Z=   .0967      10.8     9.7     8.1     6.1     4.2     2.5     1.3
```

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Z=	.1560	6.5	5.8	4.8	3.6	2.5	1.5	.8
Z=	.2442	7.5	6.6	5.4	3.8	2.4	1.3	.6

DAMAGE=-----------

	R=	.0000	.0340	.0680	.1020	.1360	.1700	.2040
Z=	.0121	.74+08	.11+08	.70+05	.17+02	.61-02	.62-04	.10-09
Z=	.0301	.75+05	.11+05	.84+02	.14+00	.10-02	.10-09	.10-09
Z=	.0569	.62+00	.14+00	.13-01	.11-02	.10-09	.10-09	.10-09
Z=	.0967	.13-02	.73-03	.27-03	.10-09	.10-09	.10-09	.10-09
Z=	.1560	.10-09	.10-09	.10-09	.10-09	.10-09	.10-09	.10-09
Z=	.2442	.40-03	.21-03	.10-09	.10-09	.10-09	.10-09	.10-09

PEAK PRESSURE= 1.0 ATM, DEPTH= .0000 CM

RADIUS OF DAMAGE= .1142 CM

DEPTH OF DAMAGE= .0558 CM

DEGREE OF BURN=3

#FIN

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```
-------------DATA CARDS(SET 2,12 CO2 PULSES GROUPED)-----------

-------------DATA CARD NUMBER 1-----------------
 3 8.56+2 1.33-4 1.36-3  2.2-1  3.7-1  6.3-1  9.5-1   2.-1   8.-1   5.-2
-------------DATA CARD NUMBER 2-----------------
1.05+0   5.-1 1.03+0  9.8-1 1.21-2   6.-3 1.31+2   1.+2   2.-2
-------------DATA CARD NUMBER 3-----------------
 .0135  .0978    3.0
-------------DATA CARD NUMBER 4-----------------
  1.0      0.  .0118      0.
-------------DATA CARD NUMBER 5-----------------
   0.  .0060  .0121  .1779    37.     22.    .006
-------------DATA CARD NUMBER 6-----------------
 149. 50000.   242. 80000.
-------------DATA CARDS NUMBER 7----------------
 100.0  119.6  132.9  142.9  151.1  158.1  164.2  169.5  174.5  179.0
 183.2  187.1  190.7  194.1  197.4  200.4  203.4  206.1  208.8  211.4
 213.9  216.2  218.5  220.8  222.9  225.0  227.0
-------------DATA CARD NUMBER 8-----------------
 3 8.56+2  2.0-4  7.0-4   0.+0   1.-2
-------------DATA CARD NUMBER 9-----------------
 .048  .1420    3.0
-------------DATA CARD NUMBER 10----------------
 837.   856.   856.
-------------DATA CARD NUMBER 11----------------
    1    100
-------------DATA CARD NUMBER 12,GAUSS----------
 .383   .135      5     15
-------------DATA CARD NUMBER 13----------------
 10.6   1.30     .5   1.00      1      12      1     20
-------------DATA CARD NUMBER 14,NC,X-----------
    3    20.    .02     6.
-------------DATA CARDS NUMBER 14,NC,GP---------
    9
    1      2      1      1      3      1      1      1      1
    1      0      0      7      0      0      2      1      1
-------------DATA CARD NUMBER 15----------------
   15
-------------DATA CARD NUMBER 16----------------
    1      7      1      7      1      0      1
-------------DATA CARD NUMBER 17----------------
 0.+0
-------------DATA CARD NUMBER 18----------------
 1.+2
-------------DATA CARD NUMBER 19----------------
    4  1.0+0  1.0+0  1.0+0  1.0+0
-------------DATA CARD NUMBER 20----------------
 1.-1  1.0+0  1.0+4  4.0+2
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```
@XQT*F E.MAINA
 ZA=  1.00  1.00  1.00  1.00

 DBI=  .1000+00  .1000+1  .1000+05  .4000+3
 DTX=
   .100-01   .100-01   .130-01   .170-01   .251-01   .326-01   .424-01   .100-01
   .100-01   .130-01   .170-01   .100-01   .100-01   .130-01   .170-01   .242-01
   .315-01   .410-01   .533-01   .100-01   .100-01   .130-01   .170-01   .100-01
   .100-01   .130-01   .170-01   .100-01   .100-01   .130-01   .170-01   .100-01
   .100-01   .130-01   .170-01   .336-01   .437-01   .568-01   .739-01   .960-01
   .125+00   .162+00   .211+00   .274+00   .357+00   .464+00   .603+00   .783+00
   .102+01   .132+01   .172+01   .224+01   .291+01   .378+01   .492+01
 POWER=
   .600+01   .600+01   .000      .000      .240+01   .240+01   .240+01   .600+01
   .600+01   .000      .000      .600+01   .600+01   .000      .000      .240+01
   .240+01   .240+01   .240+01   .600+01   .600+01   .000      .000      .600+01
   .600+01   .000      .000      .600+01   .600+01   .000      .000      .600+01
   .600+01   .000      .000      .000      .000      .000      .000      .000
   .000      .000      .000      .000      .000      .000      .000      .000
   .000      .000      .000      .000      .000      .000      .000
 XP=
        1.        1.        1.        1.        0.        0.        0.        0.
        0.        0.        0.        7.        7.        7.        7.        0.
        0.        0.        0.        0.        0.        0.        0.        2.
        2.        2.        2.        1.        1.        1.        1.        1.
        1.        1.        1.        1.        1.        1.        1.        1.
        1.        1.        1.        1.        1.        1.        1.        1.
        1.        1.        1.        1.        1.        1.        1.
 R=
     .0000     .0766     .1532     .2298     .3064     .3830     .4596     .5362
     .6128     .6894     .7660     .8426     .9192     .9958    1.0724    1.1490
 Z=
     .0000     .0121     .0253     .0397     .0553     .0724     .0910     .1113
     .1335     .1576     .1839     .2125     .2437     .2778     .3149     .3554

 SIGMA= .383+00
 HR=
   .103+01   .949+00   .746+00   .500+00   .285+00   .139+00   .575-01   .203-01
   .611-02   .156-02   .342-03   .635-04   .101-04   .136-05   .156-06
 ABSC=   856.  ABSW=   856.  CB=  1.000  CON1=  .00013  CON2=  .00134
 D0= 1.050  D1=  .500  D2= 1.030  D3=  .980  DEPID=  .0060
 HAIR=    .00  REF=    .01  SH0=  .2200  SH1=  .3700  SH2=  .6300
 TDERM=  .1779  TE=  22.  TEPID=  .0121  TO=  37.  TSWEAT=  .0000
 W0=  .950  W1=  .200  W2=  .800  W3=  .050  WAVEL=10.600
 XC= 1.300  ZDEP=  .006  ZR=   .5  ZZ=   1.00
 IPROF=1  LASER=1  LB= 3  LZ= 3  N=15  N1= 5  M=15  M1= 1
 NPULSE=  12  NGX=1  NTX=20
 ZBL= .121-01  HW= .600-02  DTEMP=  131.  DHF= .100+03
 SHF= .200-01
 CUT=   .1350  RIM=   .3830
 DPULSE=  .200-01  NTP= 3  POWX=  .600+01
 NPG=
      1       2       1       1       3       1       1       1       1
 NPR=
      1       0       0       7       0       0       2       1       1
 REPET= .2000+02
 ID1= 1  ID2= 7  ITYPE= 1  JD1= 1  JD2= 7  KTYPE=0
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```
TIME1-2=
 .000     .100+03
TH=
  .0460   .1420 3.0000
ABS=
   837.    856.    856.
TB=
  .0135   .0978 3.0000
BL=
  .0000   .0118   .0000
DAM(1,1)= 149.0  DAM(1,2)=50000.  DAM(2,1)= 242.0  DAM(2,2)=80000.
DR= .0766  RN= 1.0135  DZ= .0121  ZM=   .3554  NG= 9
CON=
    .0011    .0012    .0012    .0012    .0012    .0012    .0012    .0012
    .0012    .0012    .0012    .0002    .0002    .0002    .0002    .0002
VSH=
    .7416    .8851    .8851    .8851    .8851    .8851    .8851    .8851
    .8851    .8851    .8851    .3941    .3941    .3941    .3941    .3941
HEAT DEPOSITION RATES=----------
           R=    .0000    .0766    .1532    .2298    .3064    .3830    .4596
Z=    .0000   .169+03 .156+03 .123+03 .821+02 .469+02 .228+02 .945+01
Z=    .0121   .514+00 .475+00 .373+00 .250+00 .143+00 .694-01 .288-01
Z=    .0253   .119-04 .110-04 .867-05 .581-05 .332-05 .161-05 .668-06
Z=    .0397   .107-09 .988-10 .777-10 .521-10 .297-10 .145-10 .599-11
Z=    .0553   .000    .000    .000    .000    .000    .000    .000
Z=    .0724   .000    .000    .000    .000    .000    .000    .000
Z=    .0910   .000    .000    .000    .000    .000    .000    .000

DT= .100-01  TIME= .1000-01  POWER=  .600+01  XP=  1.  IMAX=15  JMAX=15
           R=    .0000    .0766    .1532    .2298    .3064    .3830    .4596
Z=    .0000       12.4     11.4      9.0      6.0      3.4      1.7       .7
Z=    .0121         .5       .5       .4       .3       .1       .1       .0
Z=    .0253         .0       .0       .0       .0       .0       .0       .0
Z=    .0397         .0       .0       .0       .0       .0       .0       .0
Z=    .0553         .0       .0       .0       .0       .0       .0       .0
Z=    .0724         .0       .0       .0       .0       .0       .0       .0
Z=    .0910         .0       .0       .0       .0       .0       .0       .0

DT= .100-01  TIME= .2000-01  POWER=  .600+01  XP=  1.  IMAX= 0  JMAX= 0
           R=    .0000    .0766    .1532    .2298    .3064    .3830    .4596
Z=    .0000       22.6     20.8     16.4     11.0      6.3      3.0      1.3
Z=    .0121        1.9      1.7      1.4       .9       .5       .3       .1
Z=    .0253         .1       .1       .1       .0       .0       .0       .0
Z=    .0397         .0       .0       .0       .0       .0       .0       .0
Z=    .0553         .0       .0       .0       .0       .0       .0       .0
Z=    .0724         .0       .0       .0       .0       .0       .0       .0
Z=    .0910         .0       .0       .0       .0       .0       .0       .0

DT= .130-01  TIME= .3304-01  POWER=  .000     XP=  1.  IMAX= 0  JMAX= 0
           R=    .0000    .0766    .1532    .2298    .3064    .3830    .4596
Z=    .0000       17.7     16.3     12.9      8.6      4.9      2.4      1.0
Z=    .0121        3.6      3.3      2.6      1.7      1.0       .5       .2
Z=    .0253         .3       .3       .2       .2       .1       .0       .0
Z=    .0397         .0       .0       .0       .0       .0       .0       .0
Z=    .0553         .0       .0       .0       .0       .0       .0       .0
Z=    .0724         .0       .0       .0       .0       .0       .0       .0
Z=    .0910         .0       .0       .0       .0       .0       .0       .0
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```
DT= .170-01  TIME= .5000-01  POWER=  .000      XP=   1.  IMAX= 0  JMAX= 0
            R=   .0000   .0766   .1532   .2298   .3064   .3830   .4596
Z=   .0000       13.6    12.5     9.8     6.6     3.8     1.8      .7
Z=   .0121        4.7     4.4     3.4     2.3     1.3      .6      .3
Z=   .0253         .7      .7      .5      .3      .2      .1      .0
Z=   .0397         .1      .1      .0      .0      .0      .0      .0
Z=   .0553         .0      .0      .0      .0      .0      .0      .0
Z=   .0724         .0      .0      .0      .0      .0      .0      .0
Z=   .0910         .0      .0      .0      .0      .0      .0      .0

DT= .251-01  TIME= .7506-01  POWER=  .240+01   XP=   0.  IMAX= 0  JMAX= 0

DT= .326-01  TIME= .1076+00  POWER=  .240+01   XP=   0.  IMAX= 0  JMAX= 0

DT= .424-01  TIME= .1500+00  POWER=  .240+01   XP=   0.  IMAX= 0  JMAX= 0

DT= .100-01  TIME= .1600+00  POWER=  .600+01   XP=   0.  IMAX= 0  JMAX= 0

DT= .100-01  TIME= .1700+00  POWER=  .600+01   XP=   0.  IMAX= 0  JMAX= 0

DT= .130-01  TIME= .1830+00  POWER=  .000      XP=   0.  IMAX= 0  JMAX= 0

DT= .170-01  TIME= .2000+00  POWER=  .000      XP=   0.  IMAX= 0  JMAX= 0

DT= .100-01  TIME= .2100+00  POWER=  .600+01   XP=   7.  IMAX= 0  JMAX= 0
LMI=  0  LNJ=  0  ID=  3  JD=  5
            R=   .0000   .0766   .1532   .2298   .3064   .3830   .4596
Z=   .0000       44.1    40.6    31.9    21.4    12.2     5.9     2.4
Z=   .0121       20.2    18.6    14.6     9.8     5.6     2.7     1.1
Z=   .0253        7.6     7.0     5.5     3.7     2.1     1.0      .4
Z=   .0397        2.2     2.0     1.6     1.0      .6      .3      .1
Z=   .0553         .5      .4      .3      .2      .1      .0      .0
Z=   .0724         .1      .1      .0      .0      .0      .0      .0
Z=   .0910         .0      .0      .0      .0      .0      .0      .0

DT= .100-01  TIME= .2200+00  POWER=  .600+01   XP=   7.  IMAX= 0  JMAX= 0
LMI=  0  LNJ=  0  ID=  3  JD=  6
            R=   .0000   .0766   .1532   .2298   .3064   .3830   .4596
Z=   .0000       51.9    47.8    37.6    25.2    14.4     7.0     2.9
Z=   .0121       21.5    19.8    15.6    10.5     6.0     2.9     1.2
Z=   .0253        8.2     7.5     5.9     4.0     2.3     1.1      .4
Z=   .0397        2.4     2.2     1.7     1.2      .6      .3      .1
Z=   .0553         .5      .5      .4      .2      .1      .0      .0
Z=   .0724         .1      .1      .0      .0      .0      .0      .0
Z=   .0910         .0      .0      .0      .0      .0      .0      .0

DT= .130-01  TIME= .2330+00  POWER=  .000      XP=   7.  IMAX= 0  JMAX= 0
LMI=  0  LNJ=  0  ID=  3  JD=  5
            R=   .0000   .0766   .1532   .2298   .3064   .3830   .4596
Z=   .0000       44.6    41.1    32.4    21.7    12.4     6.0     2.5
Z=   .0121       23.0    21.1    16.6    11.2     6.4     3.1     1.3
Z=   .0253        8.9     8.2     6.5     4.3     2.5     1.2      .5
Z=   .0397        2.7     2.5     2.0     1.3      .7      .3      .1
Z=   .0553         .6      .6      .4      .3      .2      .1      .0
Z=   .0724         .1      .1      .1      .0      .0      .0      .0
Z=   .0910         .0      .0      .0      .0      .0      .0      .0
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DT= .170-01  TIME= .2500+00  POWER=  .000      XP=    7.  IMAX= 0  JMAX= 0
LMI=  2  LNJ=  1  ID=  3  JD=  5
             R=    .0000    .0766    .1532    .2298    .3064    .3830    .4596
Z=    .0000        38.1     35.0     27.6     18.5     10.6      5.1      2.1
Z=    .0121        23.7     21.8     17.2     11.5      6.6      3.2      1.3
Z=    .0253         9.9      9.1      7.2      4.8      2.8      1.3       .5
Z=    .0397         3.2      2.9      2.3      1.5       .9       .4       .1
Z=    .0553          .8       .7       .6       .4       .2       .1       .0
Z=    .0724          .1       .1       .1       .0       .0       .0       .0
Z=    .0910          .0       .0       .0       .0       .0       .0       .0

DT= .242-01  TIME= .2742+00  POWER=  .240+01  XP=    0.  IMAX= 0  JMAX= 0

DT= .315-01  TIME= .3058+00  POWER=  .240+01  XP=    0.  IMAX= 0  JMAX= 0

DT= .410-01  TIME= .3467+00  POWER=  .240+01  XP=    0.  IMAX= 0  JMAX= 0

DT= .533-01  TIME= .4000+00  POWER=  .240+01  XP=    0.  IMAX= 0  JMAX= 0

DT= .100-01  TIME= .4100+00  POWER=  .600+01  XP=    0.  IMAX= 0  JMAX= 0

DT= .100-01  TIME= .4200+00  POWER=  .600+01  XP=    0.  IMAX= 0  JMAX= 0

DT= .130-01  TIME= .4330+00  POWER=  .000      XP=    1.  IMAX= 1  JMAX= 2
LMI=  2  LNJ=  2  ID=  4  JD=  6
             R=    .0000    .0766    .1532    .2298    .3064    .3830    .4596
Z=    .0000        58.1     55.5     44.5     29.9     17.1      8.3      3.4
Z=    .0121        35.7     33.4     26.5     17.8     10.2      5.0      2.0
Z=    .0253        18.9     17.4     13.7      9.2      5.3      2.6      1.0
Z=    .0397         8.7      7.9      6.2      4.2      2.4      1.1       .4
Z=    .0553         3.3      3.0      2.3      1.6       .9       .4       .1
Z=    .0724         1.0       .9       .7       .4       .2       .1       .0
Z=    .0910          .2       .2       .1       .1       .0       .0       .0

DT= .170-01  TIME= .4500+00  POWER=  .000      XP=    1.  IMAX= 0  JMAX= 0
LMI=  2  LNJ=  3  ID=  4  JD=  6
             R=    .0000    .0766    .1532    .2298    .3064    .3830    .4596
Z=    .0000        49.8     48.7     39.0     26.2     15.0      7.3      3.0
Z=    .0121        35.9     33.9     26.9     18.1     10.4      5.1      2.1
Z=    .0253        19.7     18.2     14.4      9.7      5.5      2.7      1.1
Z=    .0397         9.2      8.4      6.6      4.5      2.5      1.2       .5
Z=    .0553         3.5      3.2      2.5      1.7      1.0       .4       .2
Z=    .0724         1.1      1.0       .8       .5       .3       .1       .0
Z=    .0910          .2       .2       .2       .1       .0       .0       .0

DT= .100-01  TIME= .4600+00  POWER=  .600+01  XP=    1.  IMAX= 0  JMAX= 0
LMI=  2  LNJ=  3  ID=  4  JD=  6
             R=    .0000    .0766    .1532    .2298    .3064    .3830    .4596
Z=    .0000        59.6     57.3     45.6     30.6     17.6      8.6      3.5
Z=    .0121        38.3     34.3     27.2     18.3     10.5      5.1      2.1
Z=    .0253        20.2     18.7     14.8      9.9      5.7      2.8      1.1
Z=    .0397         9.5      8.7      6.9      4.6      2.6      1.3       .5
Z=    .0553         3.7      3.4      2.7      1.8      1.0       .5       .2
Z=    .0724         1.1      1.0       .8       .5       .3       .1       .0
Z=    .0910          .3       .2       .2       .1       .0       .0       .0

DT= .100-01  TIME= .4700+00  POWER=  .600+01  XP=    1.  IMAX= 0  JMAX= 0
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```
LMI=  2  LNJ=  3  ID=  4  JD=  6
          R=   .0000   .0766   .1532   .2298   .3064   .3830   .4596
Z=   .0000      63.0    63.0    51.1    34.3    19.6     9.6     3.9
Z=   .0121      37.1    35.2    28.0    18.8    10.8     5.3     2.2
Z=   .0253      20.7    19.2    15.2    10.2     5.8     2.8     1.2
Z=   .0397       9.9     9.0     7.1     4.8     2.7     1.3      .5
Z=   .0553       3.9     3.6     2.8     1.9     1.1      .5      .2
Z=   .0724       1.2     1.1      .9      .6      .3      .1      .0
Z=   .0910        .3      .3      .2      .1      .0      .0      .0

DT= .130-01  TIME= .4830+00  POWER=  .000     XP=   1.  IMAX= 1  JMAX= 2
LMI=  2  LNJ=  3  ID=  4  JD=  6
          R=   .0000   .0766   .1532   .2298   .3064   .3830   .4596
Z=   .0000      56.6    56.2    45.5    30.6    17.5     8.5     3.5
Z=   .0121      37.8    36.1    28.8    19.4    11.1     5.4     2.2
Z=   .0253      21.3    19.8    15.7    10.5     6.1     2.9     1.2
Z=   .0397      10.3     9.4     7.5     5.0     2.9     1.4      .5
Z=   .0553       4.1     3.8     3.0     2.0     1.1      .5      .2
Z=   .0724       1.3     1.2      .9      .6      .3      .1      .0
Z=   .0910        .3      .3      .2      .1      .1      .0      .0

DT= .170-01  TIME= .5000+00  POWER=  .000     XP=   1.  IMAX= 0  JMAX= 0
LMI=  2  LNJ=  3  ID=  4  JD=  6
          R=   .0000   .0766   .1532   .2298   .3064   .3830   .4596
Z=   .0000      50.7    50.0    40.3    27.1    15.6     7.6     3.1
Z=   .0121      37.9    36.3    29.0    19.6    11.2     5.5     2.3
Z=   .0253      22.0    20.6    16.3    11.0     6.3     3.1     1.2
Z=   .0397      10.8    10.0     7.9     5.3     3.0     1.5      .6
Z=   .0553       4.4     4.1     3.2     2.1     1.2      .6      .2
Z=   .0724       1.5     1.3     1.0      .7      .4      .2      .0
Z=   .0910        .4      .3      .2      .2      .1      .0      .0

DT= .100-01  TIME= .5100+00  POWER=  .600+01  XP=   1.  IMAX= 0  JMAX= 0
LMI=  2  LNJ=  3  ID=  4  JD=  6
          R=   .0000   .0766   .1532   .2298   .3064   .3830   .4596
Z=   .0000      60.8    58.8    47.1    31.7    18.2     8.9     3.6
Z=   .0121      38.2    36.6    29.3    19.7    11.3     5.5     2.3
Z=   .0253      22.4    21.0    16.7    11.2     6.4     3.1     1.3
Z=   .0397      11.2    10.3     8.1     5.5     3.1     1.5      .6
Z=   .0553       4.6     4.2     3.3     2.2     1.3      .6      .2
Z=   .0724       1.5     1.4     1.1      .7      .4      .2      .0
Z=   .0910        .4      .4      .3      .2      .1      .0      .0

DT= .100-01  TIME= .5200+00  POWER=  .600+01  XP=   1.  IMAX= 0  JMAX= 0
LMI=  2  LNJ=  3  ID=  4  JD=  6
          R=   .0000   .0766   .1532   .2298   .3064   .3830   .4596
Z=   .0000      63.0    63.0    52.7    35.4    20.3     9.9     4.1
Z=   .0121      38.9    37.4    30.0    20.2    11.6     5.7     2.3
Z=   .0253      22.8    21.4    17.0    11.5     6.6     3.2     1.3
Z=   .0397      11.5    10.6     8.4     5.6     3.2     1.6      .6
Z=   .0553       4.8     4.4     3.5     2.3     1.3      .6      .2
Z=   .0724       1.6     1.5     1.2      .8      .4      .2      .0
Z=   .0910        .4      .4      .3      .2      .1      .0      .0

DT= .130-01  TIME= .5330+00  POWER=  .000     XP=   1.  IMAX= 1  JMAX= 2
LMI=  2  LNJ=  3  ID=  4  JD=  6
          R=   .0000   .0766   .1532   .2298   .3064   .3830   .4596
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Z=    .0000      57.0    56.7    47.2    31.7    18.2     8.9     3.7
Z=    .0121      39.5    38.1    30.8    20.7    11.9     5.8     2.4
Z=    .0253      23.3    22.0    17.5    11.8     6.6     3.3     1.3
Z=    .0397      11.9    11.0     8.7     5.9     3.4     1.6      .6
Z=    .0553       5.1     4.7     3.7     2.5     1.4      .6      .2
Z=    .0724       1.8     1.6     1.2      .8      .4      .2      .1
Z=    .0910        .5      .4      .3      .2      .1      .0      .0

DT= .170-01  TIME= .5500+00  POWER=  .000     XP=  1.  IMAX= 0  JMAX= 0
LMI=  2  LNJ=  3  ID=  4  JD=  6
             R=  .0000   .0766   .1532   .2298   .3064   .3830   .4596
Z=    .0000      51.5    50.9    42.1    28.4    16.3     7.9     3.3
Z=    .0121      39.5    38.2    31.0    20.9    12.0     5.9     2.4
Z=    .0253      24.0    22.7    18.1    12.2     7.0     3.4     1.4
Z=    .0397      12.4    11.5     9.1     6.1     3.5     1.7      .7
Z=    .0553       5.4     5.0     3.9     2.6     1.5      .7      .3
Z=    .0724       1.9     1.7     1.4      .9      .5      .2      .1
Z=    .0910        .5      .5      .4      .2      .1      .0      .0

DT= .100-01  TIME= .5600+00  POWER=  .600+01  XP=  1.  IMAX= 0  JMAX= 0
LMI=  2  LNJ=  3. ID=  4  JD=  6
             R=  .0000   .0766   .1532   .2298   .3064   .3830   .4596
Z=    .0000      61.8    50.9    48.9    32.9    18.9     9.2     3.8
Z=    .0121      39.7    38.4    31.2    21.0    12.1     5.9     2.4
Z=    .0253      24.3    23.0    18.4    12.4     7.1     3.5     1.4
Z=    .0397      12.7    11.8     9.4     6.3     3.6     1.7      .7
Z=    .0553       5.6     5.1     4.1     2.7     1.5      .7      .3
Z=    .0724       2.0     1.8     1.4      .9      .5      .2      .1
Z=    .0910        .6      .5      .4      .2      .1      .0      .0

DT= .100-01  TIME= .5760+00  POWER=  .600+01  XP=  1.  IMAX= 0  JMAX= 0
LMI=  2  LNJ=  3  ID=  4  JD=  6
             R=  .0000   .0766   .1532   .2298   .3064   .3830   .4596
Z=    .0000      63.0    63.0    54.5    36.7    21.0    10.3     4.2
Z=    .0121      40.4    39.1    31.9    21.5    12.3     6.0     2.5
Z=    .0253      24.7    23.4    18.7    12.6     7.3     3.5     1.4
Z=    .0397      13.0    12.1     9.6     6.5     3.7     1.8      .7
Z=    .0553       5.8     5.3     4.2     2.8     1.6      .8      .3
Z=    .0724       2.1     1.9     1.5     1.0      .5      .2      .1
Z=    .0910        .6      .5      .4      .3      .1      .0      .0

DT= .330-01  TIME= .6036+00  POWER=  .000     XP=  1.  IMAX= 1  JMAX= 2
LMI=  3  LNJ=  3  ID=  4  JD=  6
             R=  .0000   .0766   .1532   .2298   .3064   .3830   .4596
Z=    .0000      50.7    50.3    42.7    28.8    16.5     8.1     3.3
Z=    .0121      40.8    39.8    32.9    22.2    12.8     6.2     2.6
Z=    .0253      25.8    24.6    19.8    13.4     7.7     3.8     1.5
Z=    .0397      14.0    13.1    10.5     7.1     4.0     2.0      .8
Z=    .0553       6.5     6.0     4.7     3.2     1.8      .8      .3
Z=    .0724       2.4     2.2     1.8     1.2      .6      .3      .1
Z=    .0910        .7      .7      .5      .3      .2      .1      .0

DT= .437-01  TIME= .6473+00  POWER=  .000     XP=  1.  IMAX= 0  JMAX= 0
LMI=  3  LNJ=  3  ID=  5  JD=  5
             R=  .0000   .0766   .1532   .2298   .3064   .3830   .4596
Z=    .0000      43.5    42.7    35.8    24.2    13.9     6.8     2.8
Z=    .0121      38.7    37.7    31.3    21.2    12.2     6.0     2.5
```

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Z= .0253	26.7	25.5	20.8	14.1	8.1	3.9	1.6
Z= .0397	15.2	14.3	11.5	7.8	4.4	2.2	.9
Z= .0553	7.3	6.8	5.4	3.6	2.1	1.0	.4
Z= .0724	2.9	2.7	2.1	1.4	.8	.3	.1
Z= .0910	.9	.8	.7	.4	.2	.1	.0

DT= .566-01 TIME= .7042+00 POWER= .000 XP= 1. IMAX= 0 JMAX= 0

LMI= 3 LNJ= 3 ID= 5 JD= 5

R=	.0000	.0766	.1532	.2298	.3064	.3830	.4596
Z= .0000	36.5	37.6	31.3	21.2	12.2	6.0	2.5
Z= .0121	35.7	34.6	28.7	19.5	11.2	5.5	2.3
Z= .0253	26.8	25.7	21.1	14.3	8.2	4.0	1.6
Z= .0397	16.4	15.6	12.6	8.5	4.9	2.4	.9
Z= .0553	8.4	7.8	6.3	4.2	2.6	1.1	.4
Z= .0724	3.6	3.3	2.6	1.7	1.0	.4	.1
Z= .0910	1.2	1.1	.9	.6	.3	.1	.0

DT= .739-01 TIME= .7781+00 POWER= .000 XP= 1. IMAX= 0 JMAX= 0

LMI= 3 LNJ= 3 ID= 5 JD= 5

R=	.0000	.0766	.1532	.2298	.3064	.3830	.4596
Z= .0000	34.4	33.4	27.7	18.8	10.8	5.3	2.2
Z= .0121	32.5	31.4	26.0	17.7	10.2	5.0	2.1
Z= .0253	26.1	25.1	20.6	14.0	8.1	3.9	1.6
Z= .0397	17.4	16.5	13.5	9.1	5.2	2.6	1.0
Z= .0553	9.6	9.0	7.3	4.9	2.8	1.3	.5
Z= .0724	4.4	4.1	3.2	2.2	1.2	.6	.2
Z= .0910	1.6	1.5	1.2	.8	.4	.2	.0

DT= .960-01 TIME= .8741+00 POWER= .000 XP= 1. IMAX= 0 JMAX= 0

LMI= 3 LNJ= 3 ID= 5 JD= 5

R=	.0000	.0766	.1532	.2298	.3064	.3830	.4596
Z= .0000	30.7	29.6	24.5	16.7	9.7	4.7	1.9
Z= .0121	29.5	28.3	23.4	15.9	9.2	4.5	1.9
Z= .0253	24.8	23.8	19.6	13.3	7.7	3.8	1.5
Z= .0397	17.9	17.0	13.9	9.5	5.5	2.7	1.1
Z= .0553	10.9	10.2	8.3	5.6	3.2	1.5	.6
Z= .0724	5.5	5.1	4.1	2.7	1.5	.7	.2
Z= .0910	2.2	2.1	1.6	1.1	.6	.3	.1

DT= .125+00 TIME= .9990+00 POWER= .000 XP= 1. IMAX= 0 JMAX= 0

LMI= 3 LNJ= 3 ID= 5 JD= 5

R=	.0000	.0766	.1532	.2298	.3064	.3830	.4596
Z= .0000	27.4	26.2	21.7	14.8	8.6	4.2	1.7
Z= .0121	26.5	25.3	20.9	14.3	8.3	4.1	1.7
Z= .0253	23.2	22.1	18.2	12.4	7.2	3.5	1.4
Z= .0397	17.9	17.0	13.9	9.5	5.5	2.7	1.1
Z= .0553	11.9	11.2	9.1	6.2	3.6	1.7	.7
Z= .0724	6.6	6.2	5.0	3.4	1.9	.9	.3
Z= .0910	3.1	2.8	2.3	1.5	.8	.4	.1

DAMAGE------------

R=	.0000	.0766	.1532	.2298	.3064	.3830	.4596
Z= .0121	.10+06	.47+05	.46+03	.35+00	.66-03	.10-09	.10-09
Z= .0253	.19+02	.84+01	.33+00	.25-02	.11-03	.10-09	.10-09
Z= .0397	.36-01	.19-01	.19-02	.17-03	.10-09	.10-09	.10-09
Z= .0553	.30-03	.22-03	.70-04	.10-09	.10-09	.10-09	.10-09
Z= .0724	.10-09	.10-09	.10-09	.10-09	.10-09	.10-09	.10-09
Z= .0910	.10-09	.10-09	.10-09	.10-09	.10-09	.10-09	.10-09

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```
PEAK PRESSURE=    1.0 ATM.   DEPTH=   .0000 CM
RADIUS OF DAMAGE=  .2185 CM
DEPTH OF DAMAGE=  .0320 CM
DEGREE OF BURN=3
@FIN
```

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```
-------------DATA CARDS(SET 3,CO2 CODED PULSES)---------------

    -------------DATA CARD NUMBER 1------------------
    3 8.56+2 1.33-4 1.36-3  2.2-1   3.7-1  6.3-1  9.5-1    2.-1    8.-1    5.-2
    -------------DATA CARD NUMBER 2------------------
1.05+0   5.-1 1.03+0  9.8-1 1.21-2   6.-3 1.31+2   1.+2   2.-2
    -------------DATA CARD NUMBER 3------------------
 .0135  .0978    3.0
    -------------DATA CARD NUMBER 4------------------
   1.0     0.  .0118     0.
    -------------DATA CARD NUMBER 5------------------
    0.  .0060  .0121  .1779    37.     22.    .006
    -------------DATA CARD NUMBER 6------------------
  149. 50000.   242. 80000.
    -------------DATA CARDS NUMBER 7-----------------
 100.0  119.6  132.8  142.9  151.1  158.1  164.2  169.5  174.5  179.0
 183.2  187.1  190.7  194.1  197.4  200.4  203.4  206.1  208.8  211.4
 213.9  216.2  218.5  220.8  222.9  225.0  227.0
    -------------DATA CARD NUMBER 8------------------
    3 8.56+2  2.0-4  7.0-4   0.+0    1.-2
    -------------DATA CARD NUMBER 9------------------
  .048  .1420    3.0
    -------------DATA CARD NUMBER 10-----------------
  837.   856.   856.
    -------------DATA CARD NUMBER 11-----------------
    1    100
    -------------DATA CARD NUMBER 12,GAUSS-----------
  .383   .135      5     15
    -------------DATA CARD NUMBER 13-----------------
  10.6   1.30     .5   1.00      2      3      0     20
    -------------DATA CARDS NUMBER 14,CODED----------
    4
  5.-2   1.-2   3.-2
  4.+0   1.+0   3.+0
    -------------DATA CARD NUMBER 15-----------------
   15
    -------------DATA CARD NUMBER 16-----------------
    1      7      1      7      1      0      1
    -------------DATA CARD NUMBER 17-----------------
  0.+0
    -------------DATA CARD NUMBER 18-----------------
  1.+2
    -------------DATA CARD NUMBER 19-----------------
    4  1.0+0  1.0+0  1.0+0  1.0+0
    -------------DATA CARD NUMBER 20-----------------
  1.-1  1.0+0  1.0+4  4.0+2
```

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```
@XQT,F E.MAINA
 ZW= 1.00  1.00  1.00  1.00

 DH1=  .1000+00  .1000+1  .1000+05  .4000+3
 DTX=
   .125-01  .125-01  .125-01  .125-01  .250-02  .250-02  .250-02  .250-02
   .750-02  .750-02  .750-02  .750-02  .336-01  .437-01  .568-01  .739-01
   .960-01  .125+00  .162+00  .211+00  .274+00  .357+00  .464+00  .603+00
   .783+00  .102+01  .132+01  .172+01  .224+01  .291+01  .378+01  .492+01
 POWER=
   .400+01  .400+01  .400+01  .400+01  .100+01  .100+01  .100+01  .100+01
   .300+01  .300+01  .300+01  .300+01  .000     .000     .000     .000
   .000     .000     .000     .000     .000     .000     .000     .000
   .000     .000     .000     .000     .000     .000     .000     .000
 XP=
       1.       1.       1.       1.       1.       1.       1.       1.
       1.       1.       1.       1.       1.       1.       1.       1.
       1.       1.       1.       1.       1.       1.       1.       1.
       1.       1.       1.       1.       1.       1.       1.       1.
 R=
     .0000    .0766    .1532    .2298    .3064    .3830    .4596    .5362
     .6128    .6894    .7660    .8426    .9192    .9958   1.0724   1.1490
 Z=
     .0000    .0121    .0246    .0375    .0508    .0645    .0786    .0932
     .1083    .1238    .1398    .1564    .1735    .1911    .2092    .2280

 SIGMA= .383+00
 HR=
   .103+01  .949+00  .746+00  .500+00  .245+00  .139+00  .575-01  .203-01
   .611-02  .156-02  .342-03  .635-04  .101-04  .136-05  .156-06
 ABSC=   856.  ABSH=   856.  CB= 1.000  CON1=  .00013  CON2=  .00136
 DO= 1.050  D1=  .500  D2= 1.030  D3=  .980  DEPID=  .0060
 HAIR=    .00  REF=    .01  SH0=  .2200  SH1=  .3700  SH2=  .6300
 TDERM=  .1779  TE=  22.  TEPID=  .0121  TO=  37.  TSWEAT=  .0000
 W0=  .950  W1=  .430  W2=  .800  W3=  .050  WAVEL=10.600
 XC= 1.300  ZDEP=  .006  ZR=   .5  ZZ=   1.00
 IPROF=1  LASER=2  LB= 3  LZ= 3  N=15  N1= 5  M=15  M1= 1
 NPULSE=   3  NGX=0  NTX=20
 ZBL= .121-01  HK= .600-02  DTEMP=  131.  DHF= .100+03
 SHF= .200-01
 CUT=   .1350  RIM=   .3830
 DPULSC=
  .500-01 .100-01 .500-01
 POWERC=
  .400+01 .100+01 .300+01
 ID1= 1  ID2= 7  ITYPE= 1  JD1= 1  JD2= 7  KTYPE=0
 TIME1-2=
  .000     .100+03
 TM=
   .0480  .1420 3.0000
 ABS=
    837.   856.   856.
 TB=
   .0135  .0978 3.0000
 BL=
   .0000  .0118  .0000
 DAM(1,1)= 149.0  DAM(1,2)=50000.  DAM(2,1)= 242.0  DAM(2,2)=80000.
```

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```
DR= .0766  RN=   .9498  DZ= .0121  ZM=   .2280  NG= 0
CON=
    .0011     .0012     .0012     .0012     .0012     .0012     .0012     .0012
    .0012     .0012     .0012     .0012     .0012     .0002     .0002     .0002
VSM=
    .7416     .8851     .8851     .8851     .8851     .8851     .8851     .8851
    .8851     .8851     .8851     .8851     .8851     .3941     .3941     .3941
HEAT DEPOSITION RATES=----------
           R=    .0000    .0766    .1532    .2298    .3064    .3830    .4596
Z=    .0000    .169+03 .156+03 .123+03 .821+02 .469+02 .228+02 .945+01
Z=    .0121    .529+00 .488+00 .384+00 .257+00 .147+00 .714-01 .296-01
Z=    .0246    .174-04 .161-04 .127-04 .848-05 .484-05 .235-05 .975-06
Z=    .0375    .415-09 .383-09 .301-09 .202-09 .115-09 .560-10 .232-10
Z=    .0508    .000     .000     .000     .000     .000     .000     .000
Z=    .0645    .000     .000     .000     .000     .000     .000     .000
Z=    .0786    .000     .000     .000     .000     .000     .000     .000

DT= .125-01  TIME= .1250-01  POWER=  .400+01  XP=   1.  IMAX=15  JMAX=15
           R=    .0000    .0766    .1532    .2298    .3064    .3830    .4596
Z=    .0000       10.1      9.3      7.3      4.9      2.8      1.4       .6
Z=    .0121         .5       .5       .4       .3       .1       .1       .0
Z=    .0246         .0       .0       .0       .0       .0       .0       .0
Z=    .0375         .0       .0       .0       .0       .0       .0       .0
Z=    .0508         .0       .0       .0       .0       .0       .0       .0
Z=    .0645         .0       .0       .0       .0       .0       .0       .0
Z=    .0786         .0       .0       .0       .0       .0       .0       .0

DT= .125-01  TIME= .2500-01  POWER=  .400+01  XP=   1.  IMAX= 0  JMAX= 0
           R=    .0000    .0766    .1532    .2298    .3064    .3830    .4596
Z=    .0000       18.0     16.7     13.1      8.8      5.0      2.4      1.0
Z=    .0121        1.9      1.7      1.4       .9       .5       .3       .1
Z=    .0246         .1       .1       .1       .1       .0       .0       .0
Z=    .0375         .0       .0       .0       .0       .0       .0       .0
Z=    .0508         .0       .0       .0       .0       .0       .0       .0
Z=    .0645         .0       .0       .0       .0       .0       .0       .0
Z=    .0786         .0       .0       .0       .0       .0       .0       .0

DT= .125-01  TIME= .3750-01  POWER=  .400+01  XP=   1.  IMAX= 0  JMAX= 0
           R=    .0000    .0766    .1532    .2298    .3064    .3830    .4596
Z=    .0000       24.5     22.6     17.8     11.9      6.8      3.3      1.4
Z=    .0121        3.7      3.4      2.7      1.8      1.0       .5       .2
Z=    .0246         .4       .3       .3       .2       .1       .0       .0
Z=    .0375         .0       .0       .0       .0       .0       .0       .0
Z=    .0508         .0       .0       .0       .0       .0       .0       .0
Z=    .0645         .0       .0       .0       .0       .0       .0       .0
Z=    .0786         .0       .0       .0       .0       .0       .0       .0

DT= .125-01  TIME= .5000-01  POWER=  .400+01  XP=   1.  IMAX= 0  JMAX= 0
           R=    .0000    .0766    .1532    .2298    .3064    .3830    .4596
Z=    .0000       29.9     27.6     21.7     14.5      8.3      4.0      1.7
Z=    .0121        5.7      5.3      4.2      2.8      1.6       .8       .3
Z=    .0246         .8       .7       .5       .4       .2       .1       .0
Z=    .0375         .1       .1       .0       .0       .0       .0       .0
Z=    .0508         .0       .0       .0       .0       .0       .0       .0
Z=    .0645         .0       .0       .0       .0       .0       .0       .0
Z=    .0786         .0       .0       .0       .0       .0       .0       .0
```


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```
DT= .250-02  TIME= .5250-01  POWER=  .100+01  XP=   1.  IMAX= 0  JMAX= 0
          R=   .0000    .0766    .1532    .2298    .3064    .3830    .4596
Z=   .0000     29.2     26.9     21.2     14.2      8.1      3.9      1.6
Z=   .0121      6.2      5.7      4.5      3.0      1.7       .8       .3
Z=   .0246       .9       .8       .6       .4       .2       .1       .0
Z=   .0375       .1       .1       .1       .0       .0       .0       .0
Z=   .0508       .0       .0       .0       .0       .0       .0       .0
Z=   .0645       .0       .0       .0       .0       .0       .0       .0
Z=   .0786       .0       .0       .0       .0       .0       .0       .0

DT= .250-02  TIME= .5500-01  POWER=  .100+01  XP=   1.  IMAX= 0  JMAX= 0
          R=   .0000    .0766    .1532    .2298    .3064    .3830    .4596
Z=   .0000     28.5     26.3     20.7     13.9      7.9      3.8      1.6
Z=   .0121      6.5      6.0      4.7      3.2      1.8       .9       .4
Z=   .0246       .9       .9       .7       .5       .3       .1       .0
Z=   .0375       .1       .1       .1       .0       .0       .0       .0
Z=   .0508       .0       .0       .0       .0       .0       .0       .0
Z=   .0645       .0       .0       .0       .0       .0       .0       .0
Z=   .0786       .0       .0       .0       .0       .0       .0       .0

DT= .250-02  TIME= .5750-01  POWER=  .100+01  XP=   1.  IMAX= 0  JMAX= 0
          R=   .0000    .0766    .1532    .2298    .3064    .3830    .4596
Z=   .0000     28.0     25.8     20.3     13.6      7.8      3.8      1.5
Z=   .0121      6.9      6.4      5.0      3.3      1.9       .9       .4
Z=   .0246      1.1      1.0       .8       .5       .3       .1       .1
Z=   .0375       .1       .1       .1       .0       .0       .0       .0
Z=   .0508       .0       .0       .0       .0       .0       .0       .0
Z=   .0645       .0       .0       .0       .0       .0       .0       .0
Z=   .0786       .0       .0       .0       .0       .0       .0       .0

DT= .250-02  TIME= .6000-01  POWER=  .100+01  XP=   1.  IMAX= 0  JMAX= 0
LMI=  0  LNJ=  0  ID=  2  JD=  5
          R=   .0000    .0766    .1532    .2298    .3064    .3830    .4596
Z=   .0000     27.4     25.3     19.9     13.3      7.6      3.7      1.5
Z=   .0121      7.2      6.7      5.2      3.5      2.0      1.0       .4
Z=   .0246      1.2      1.1       .8       .6       .3       .1       .1
Z=   .0375       .1       .1       .1       .1       .0       .0       .0
Z=   .0508       .0       .0       .0       .0       .0       .0       .0
Z=   .0645       .0       .0       .0       .0       .0       .0       .0
Z=   .0786       .0       .0       .0       .0       .0       .0       .0

DT= .750-02  TIME= .6750-01  POWER=  .300+01  XP=   1.  IMAX= 0  JMAX= 0
LMI=  0  LNJ=  0  ID=  2  JD=  5
          R=   .0000    .0766    .1532    .2298    .3064    .3830    .4596
Z=   .0000     29.2     27.0     21.2     14.2      8.1      3.9      1.6
Z=   .0121      8.2      7.5      5.9      4.0      2.3      1.1       .5
Z=   .0246      1.5      1.4      1.1       .7       .4       .2       .1
Z=   .0375       .2       .2       .1       .1       .0       .0       .0
Z=   .0508       .0       .0       .0       .0       .0       .0       .0
Z=   .0645       .0       .0       .0       .0       .0       .0       .0
Z=   .0786       .0       .0       .0       .0       .0       .0       .0

DT= .750-02  TIME= .7500-01  POWER=  .300+01  XP=   1.  IMAX= 0  JMAX= 0
LMI=  0  LNJ=  0  ID=  2  JD=  5
          R=   .0000    .0766    .1532    .2298    .3064    .3830    .4596
Z=   .0000     30.9     28.5     22.4     15.0      8.6      4.2      1.7
Z=   .0121      9.2      8.4      6.6      4.5      2.5      1.2       .5
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Z=	.0246	1.8	1.7	1.3	.9	.5	.2	.1
Z=	.0375	.3	.2	.2	.1	.1	.0	.0
Z=	.0508	.0	.0	.0	.0	.0	.0	.0
Z=	.0645	.0	.0	.0	.0	.0	.0	.0
Z=	.0786	.0	.0	.0	.0	.0	.0	.0

DT= .750-02 TIME= .8250-01 POWER= .300+01 XP= 1. IMAX= 0 JMAX= 0
LMI= 0 LNJ= 0 ID= 2 JD= 5

	R=	.0000	.0766	.1532	.2298	.3064	.3830	.4596
Z=	.0000	32.5	30.0	23.6	15.8	9.0	4.4	1.8
Z=	.0121	10.1	9.3	7.3	4.9	2.8	1.4	.6
Z=	.0246	2.2	2.0	1.6	1.1	.6	.3	.1
Z=	.0375	.3	.3	.2	.2	.1	.0	.0
Z=	.0508	.0	.0	.0	.0	.0	.0	.0
Z=	.0645	.0	.0	.0	.0	.0	.0	.0
Z=	.0786	.0	.0	.0	.0	.0	.0	.0

DT= .750-02 TIME= .9000-01 POWER= .300+01 XP= 1. IMAX= 0 JMAX= 0
LMI= 0 LNJ= 0 ID= 2 JD= 5

	R=	.0000	.0766	.1532	.2298	.3064	.3830	.4596
Z=	.0000	34.0	31.3	24.7	16.5	9.4	4.6	1.9
Z=	.0121	11.1	10.2	8.1	5.4	3.1	1.5	.6
Z=	.0246	2.6	2.4	1.9	1.3	.7	.3	.1
Z=	.0375	.4	.4	.3	.2	.1	.0	.0
Z=	.0508	.1	.0	.0	.0	.0	.0	.0
Z=	.0645	.0	.0	.0	.0	.0	.0	.0
Z=	.0786	.0	.0	.0	.0	.0	.0	.0

DT= .336-01 TIME= .1236+00 POWER= .000 XP= 1. IMAX= 0 JMAX= 0
LMI= 0 LNJ= 0 ID= 2 JD= 4

	R=	.0000	.0766	.1532	.2298	.3064	.3830	.4596
Z=	.0000	22.4	20.7	16.3	10.9	6.2	3.0	1.2
Z=	.0121	13.3	12.2	9.6	6.5	3.7	1.8	.7
Z=	.0246	4.3	4.0	3.1	2.1	1.2	.6	.2
Z=	.0375	1.0	.9	.7	.5	.3	.1	.0
Z=	.0508	.2	.2	.1	.1	.0	.0	.0
Z=	.0645	.0	.0	.0	.0	.0	.0	.0
Z=	.0786	.0	.0	.0	.0	.0	.0	.0

DT= .437-01 TIME= .1673+00 POWER= .000 XP= 1. IMAX= 0 JMAX= 0
LMI= 0 LNJ= 0 ID= 2 JD= 4

	R=	.0000	.0766	.1532	.2298	.3064	.3830	.4596
Z=	.0000	16.4	15.1	11.9	8.0	4.5	2.2	.9
Z=	.0121	12.7	11.7	9.2	6.2	3.5	1.7	.7
Z=	.0246	5.9	5.4	4.3	2.9	1.6	.8	.3
Z=	.0375	1.9	1.7	1.4	.9	.5	.2	.1
Z=	.0508	.5	.4	.3	.2	.1	.0	.0
Z=	.0645	.1	.1	.1	.0	.0	.0	.0
Z=	.0786	.0	.0	.0	.0	.0	.0	.0

DT= .560-01 TIME= .2242+00 POWER= .000 XP= 1. IMAX= 0 JMAX= 0
LMI= 0 LNJ= 0 ID= 2 JD= 3

	R=	.0000	.0766	.1532	.2298	.3064	.3830	.4596
Z=	.0000	13.0	11.9	9.4	6.3	3.6	1.7	.7
Z=	.0121	11.2	10.3	8.1	5.4	3.1	1.5	.6
Z=	.0246	6.8	6.2	4.9	3.3	1.9	.9	.4
Z=	.0375	2.9	2.7	2.1	1.4	.8	.4	.1

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Z=   .0508         .9        .9        .7        .4        .2        .1        .0
Z=   .0645         .2        .2        .2        .1        .0        .0        .0
Z=   .0786         .0        .0        .0        .0        .0        .0        .0

DT= .734-01  TIME= .2981+00  POWER=  .000      XP=   1.  IMAX= 0  JMAX= 0
LMI=  0  LNJ=  0  ID=  2  JD=  3
           R=    .0000     .0766     .1532     .2298     .3064     .3830     .4596
Z=   .0000       10.7       9.8       7.7       5.2       3.0       1.4        .6
Z=   .0121        9.7       8.9       7.0       4.7       2.7       1.3        .5
Z=   .0246        6.9       6.3       5.0       3.3       1.9        .9        .4
Z=   .0375        3.8       3.4       2.7       1.8       1.0        .5        .2
Z=   .0508        1.6       1.5       1.1        .8        .4        .2        .1
Z=   .0645         .5        .5        .4        .2        .1        .0        .0
Z=   .0786         .1        .1        .1        .0        .0        .0        .0

DT= .960-01  TIME= .3941+00  POWER=  .000      XP=   1.  IMAX= 0  JMAX= 0
LMI=  0  LNJ=  0  ID=  2  JD=  2
           R=    .0000     .0766     .1532     .2298     .3064     .3830     .4596
Z=   .0000        8.9       8.2       6.4       4.3       2.5       1.2        .4
Z=   .0121        8.4       7.6       6.0       4.1       2.3       1.1        .4
Z=   .0246        6.6       6.0       4.7       3.2       1.8        .9        .3
Z=   .0375        4.2       3.9       3.1       2.0       1.2        .5        .2
Z=   .0508        2.2       2.0       1.6       1.1        .6        .3        .1
Z=   .0645        1.0        .9        .7        .4        .2        .1        .0
Z=   .0786         .3        .3        .2        .1        .1        .0        .0

DT= .125+00  TIME= .5190+00  POWER=  .000      XP=   1.  IMAX= 0  JMAX= 0
LMI=  0  LNJ=  0  ID=  2  JD=  1
           R=    .0000     .0766     .1532     .2298     .3064     .3830     .4596
Z=   .0000        7.5       6.9       5.4       3.6       2.1       1.0        .4
Z=   .0121        7.2       6.6       5.2       3.5       2.0        .9        .4
Z=   .0246        6.0       5.5       4.3       2.9       1.7        .8        .3
Z=   .0375        4.4       4.0       3.2       2.1       1.2        .5        .2
Z=   .0508        2.7       2.5       2.0       1.3        .7        .3        .1
Z=   .0645        1.4       1.3       1.0        .7        .4        .1        .0
Z=   .0786         .6        .6        .4        .3        .1        .0        .0
DAMAGE===========
           R=    .0000     .0766     .1532     .2298     .3064     .3830     .4596
Z=   .0121     .46-03    .27-03    .75-04    .10-09    .10-09    .10-09    .10-09
Z=   .0246     .10-09    .10-09    .10-09    .10-09    .10-09    .10-09    .10-09
Z=   .0375     .10-09    .10-09    .10-09    .10-09    .10-09    .10-09    .10-09
Z=   .0508     .10-09    .10-09    .10-09    .10-09    .10-09    .10-09    .10-09
Z=   .0645     .10-09    .10-09    .10-09    .10-09    .10-09    .10-09    .10-09
Z=   .0786     .10-09    .10-09    .10-09    .10-09    .10-09    .10-09    .10-09
PEAK PRESSURE=    1.0 ATM.    DEPTH=    .0000 CM

DEGREE OF BURN=0

=FIN
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